Howard Jacobs SA23

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SPECIFICATION NO. DVS-30
Revision 3
21 April 1989

SSME ALTERNATE TURBOPUMP DEVELOPMENT PROGRAM

DESIGN VERIFICATION SPECIFICATION FOR HIGH-PRESSURE FUEL TURBOPUMP

Prepared Under
NASA Contract NAS8-36801
DRL Sequence No. SE06
WBS No. 1.5.1.1.1

Prepared for
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812

Prepared by
Pratt & Whitney
P. O. Box 109600
West Palm Beach, FL 33410-9600

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HIGH-PRESSURE FUEL TURBOPUMP

1.0 SCOPE

1.1 The purpose of this document is to define the design and verification requirements appropriate to hardware at the detail, subassembly, component, and engine levels and to correlate these requirements to the development demonstrations which provides verification that design objectives are achieved. This document will be expanded and updated by document revisions as HPFTP design requirements and environmental predictions are refined.

The Design Verification Specification is constructed from critical substantiation criteria extracted from the Contract End Item (CEI) Specification, Interface Control Document (ICD), and from collected Engineering Verification requirements. Engineering Verification requirements are derived from a design assumption or uncertainty which must be substantiated through analysis or test to ensure the design performs as predicted.

Verification Requirements are identified by Design Engineers, Development Engineers, Analytical Design Specialists, etc., using the Verification/Substantiation Requirement (V/SR) form. A properly completed form describes the Verification Requirement, including probable distress/dysfunction modes in service, testing required, success criteria, scheduled completion date, and (after completion) a summary of the results, including approvals of verification completion. P&W internal approvals that Verification Requirements have been met are required from the Analytical Design Specialist, Lead WBS Manager, Engineering Manager, and the Safety, Reliability, and Quality Assurance (SR & QA) Manager.

All completed V/SR forms are submitted to the DVS Group of RMS Engineering for tracking and coordination. Meetings are conducted as required to determine the validity and priority of the Verification Requirements. These meetings are composed of representatives from Design, Project, Analytical, and Design Support Groups. All approved Verification Requirements are included in the appropriate DVS and are scheduled into the overall Development Test Plan. If agreement cannot be reached on the validity of a requirement, the issue is raised to the ATD Program Engineering Manager for final decision.

SECTION 2.0
APPLICABLE DOCUMENTS

2.0 APPLICABLE DOCUMENTS

The following documents are within the text of this Design Verification Specification (DVS) and are applicable to the extent specified.

SPECIFICATIONS

MIL-T-152B Amendment 2 6 June 1966	Treatment, Moisture and Fungus-Resistant, of Communications, Electronic, and Associated Equipment
MIL-B-5087B Amendment 2 31 August 1970	Bonding, Electrical, and Lightning Protection, for Aerospace Systems
MIL-E-6051D Amendment 1 5 July 1968	Electromagnetic Compatibility Requirements System
MIL-S-7742B 2 February 1968	Screw Threads, Standard, Optimum Selected Series, General Specification for
MIL-B-7883B	Brazing of Steels, Copper, Copper Alloy, Nickel Alloys, Aluminum and Aluminum Alloys
MIL-S-8879A Amendment 1 15 March 1973	ScrewThreads, Controlled Radius Root with Increased Minor Diameter; General Specification for
MIL-W-22759D Amendment 1 7 December 1979	Wire, Electric, Fluoropolymer Insulated, Copper or Copper Alloy
MIL-P-27201B 30 June 1971	Propellant, Hydrogen
MIL-P-27401C	Propellant Pressurizing Agent, Nitrogen
MIL-P-27407A 28 November 1978	Propellant Pressurizing Agent, Helium
MIL-H-83282B Int. Amendment 1 10 September 1976	Hydraulic Fluid, Fire Resistant Synthetic Hydrocarbon Base, Aircraft

GEORGE C. MARSHALL SPACE FLIGHT CENTER

MSFC-SPEC-250A 1 October 1977	Protective Finishes for Space Vehicle Structures and Associated Flight Equipment General Specification for
MSFC-SPEC-278B Amendment 1 21 February 1968	Terminals, Solder, Swage-Types and Insulated Screw-Types
MSFC-SPEC-527 (Latest Revision)	Material Selection, Guide for MSFC Spacelab Payloads
MSFC-SPEC-560	Welding, Steels, Corrosion and Heat Resistant
MSFC-STD-655	Standard Weld Filler Metal, Control of
MSFC-STD-505A	Structural Strength Program Requirements
MSFC-STD-506B	Standard Materials and Processes Control
MSFC-STD-1249	Standard NDE Guidelines and Requirements for Fracture Control Program
NHB 8060.1B September 1981	Flammability, Odor and Off Gassing Requirements and Test Procedures for Materials in Environments that Support Combustion
NAS 1113	Requirements for Materials Exposed to High Pressure LOX/GOX
MSFC-SPEC-522A 20 August 1975	Design Criteria for Controlling Stress Corrosion Cracking
40M39513C 29 October 1981	Wire, Electrical, Hookup, General Specification for
40M39526C 18 June 1973	Cable, Electrical, Shielded, Jacketed Specification for
40M50577 EO's 2 & 3 4 September 1973	Wire, Electrical, Shielded, Nickel-Coated TFE Insulated and Jacketed, Specification for
85M02704F EO 13 16 September 1976	Microcircuits, Quality Assurance and Screening Requirements for, High Reliability

85M03928C 12 May 1983	Electronic, Electrical, and Electromechanical Parts Selection and Control Requirements for Space Shuttle Engines
NHB 6000.1	Packing, Packaging, Identification and Marking and Preparation for Shipment of Materials, Components and End Items
85M03766F 11 August 1977	Microcircuit, Monolithic Silicon Transistor - Transistor Logic (TTL), Family of Devices, Specification Control Drawing for

LYNDON B. JOHNSON SPACE CENTER

SL-E-0002A 16 September 1974	Electromagnetic Interference Characteristics,Requirements for Equipment
SE-S-0073C 14 February 1977	Space Shuttle Fluid Procurement and Use Control

STANDARDS

MIL-STD-130F 5 August 1977	Identification Marking of US Military Property
MIL-STD-461B 1 April 1980	Electromagnetic Interference Characteristics Requirements for Equipment
MIL-STD-462 Notices 1 & 2 1 May 1970	Electromagnetic Interference Characteristics Measurement of
MIL-STD-1247B 20 December 1968	Markings, Functions and Hazard Designations of Hose, Pipe, and Tube Lines for Aircraft, Missile, and Space Systems
MIL-STD-1276C Notice 1 - 9/2/80 Notice 2 - 1/18/82	Leads, Weldable, for Electronic Component Parts
10M33107B 30 August 1975	Design Guidelines for Controlling Stress Corrosion Cracking
20M02540B 25 September 1979	Assessment of Flexible Lines for Flow Induced Vibration

85M03885 16 September 1971	Guidelines for Performing Faliure Mode, Effects and Criticality Analysis (FMECA) On the Space Shuttle

ROCKETDYNE SPECIFICATIONS

RL10001F 13 February 1981	Cleanliness of Components for Use in Oxygen, Fuel, and Pneumatic Systems, Specification for
RL10003 24 November 1971	Castings, Aluminum Alloy, Radiographic Inspection of, Acceptance Standard for
RL10005B 25 March 1974	Printed Wiring Boards (Copper Clad) Design, Documentation, and Fabrication of
RL10006C 19 August 1982	Fabrication of Welded Electronic Modules Standard for
RL10007B 17 January 1976	Terminals, Installation of, Procedure for
RL10008F 3 January 1978	Plastics and Elastomers for Electrical Encapsulation and Coatings
RL10009E 19 August 1982	Requirements for Soldered Electrical Connections
RL10011H 19August 1982	Fusion Welding for SSME, Process and Quality Requirements
RL10012D 28 October 1982	Hydraulic systems Detailed Parts, Components, Assemblies, and Hydraulic Fluids for Space Vehicles, Cleaning, Testing and Handling
RL10013D 13 February 1981	Installation of Harness Assembly (Electrical Wiring), Space Vehicle, General Specification for
RL10014G 13 February 1981	Harness, Electrical Design Standard
RL10017B 13 February 1981	Oxygen System and Flammability Material Usage Agreements
CP320R003	SSME CEI Specification
RS007001	Rocket Engine Assembly, SSME

RS007002	Powerhead, Thrust Chamber, and Turbopump Installation
RS007003	Propellant Feed System Articulating Installation
RS007004	Propellant Feed System Fixed Installation
RS007005	Hydraulic and Pneumatic System Installation
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RS007007	Electrical System Installation
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CP11370A	CEI Specification HPFTP
CP11372	ICD Specification HPFTP
FTDM 2624	P&W Structural Design Criteria
PWA 16 AK	Weld-Arc, Gas, Electron Beam, Laser Beam, and Inertia-Friction
FR 19793-1	P&W Fracture Control Plan
FR 19683-2	Program Development Plan
FR 19673-2	P&W Materials Control Plan
FR 19685-1	P&W Manufacturing Plan
FR 19678-2A	P&W Configuration Management Plan
ATD-PBM-587	SSME Power Balance Model
ATD-DTM-587	SSME Digital Transient Model

SECTION 3.0
DESIGN REQUIREMENTS

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3.0 DESIGN REQUIREMENTS

The design requirements for the HPFTP are given in this section. The requirement source index is presented in Table III-1.

3.1 Functional and Nonoperating Characteristics

3.1.1 Functional Performance. The high-pressure fuel turbopump, when applied in the SSME engine system, shall be capable of delivering the pressures and flow rates to the engine required to meet the engine system performance requirements specified by CEI Specification after being subjected to the purges defined by the ICD.

3.1.1.1 Power Levels. The turbopump shall meet the requirements of the engine Minimum Power Level (MPL), Rated Power Level (RPL), and Full Power Level (FPL) as specified in the CEI CP11370. MPL and FPL shall also be referred to as 65% RPL and 109% RPL, respectively.

3.1.1.2 Shutdown/Throttling/Step Change. The turbopump shall meet the requirements of the engine to:

a. Shutdown from any power level in a safe manner according to HPFTP ICD Specification CP 11372.

b. Throttle and step change between FPL and MPL and any power levels according to HPFTP ICD Specification CP 11372.

3.1.1.3 Starts. The turbopump shall meet the following engine requirements:

a. Single, sea level start per mission duty cycle.

b. Starting schedule according to HPFTP ICD Specification CP11372.

c. The turbopump shall be capable of starting once after each ground servicing.

3.1.1.4 RPL/MPL Durations. The turbopump shall function continuously at any engine power level between MPL and RPL for a period of at least 823 seconds.

3.1.1.5 FPL Durations. The turbopump shall be capable of continuous operation up to and including FPL for a period of at least 754 seconds.

3.1.1.6 Propellant. The turbopump shall pump liquid hydrogen supplied by the low pressure pump according to HPFTP ICD Specification CP11372.

3.1.1.7 Leakage. Under static conditions with the turbopump conditioned for start, the internal leakage shall not exceed TBD scim of hydrogen. The turbopump shall be designed to prevent external leakage of greater than 7×10^{-2} scc/sec Helium at leak check pressure at separable joints.

3.1.1.8 Prelaunch Conditioning Duration. The turbopump shall achieve required Prestart thermal conditioning without ground servicing within 60 minutes from the time propellants are supplied to the turbopump. The bleed flow through the pump to be provided for this purpose is defined in the ICD.

3.1.1.9 Prelaunch Service Free Duration. The turbopump shall function at any time without ground servicing under propellant loaded conditions within a period of no greater than 24 hours.

3.1.1.10 Duty Cycle Requirements. The high-pressure fuel turbopump shall be designed to operating without overhaul for 7.5 hours at the maximum combination of temperature, speeds, and loads consistent with the design margins of CEI Specification 11370. The turbopump shall perform 60 starts and associated mission power level profile to any power level including 109% RPL without overhaul.

3.1.1.11 Drying Purge. The design shall provide the capability to remove propellant combustion products (water) from the turbopump at the completion of a mission.

3.1.1.12 Thermal Insulation Requirements. Insulation shall be applied to critical areas of the high-pressure fuel turbopump to ensure that liquid air shall not form during ground conditioning or flight.

3.1.1.13 Breakaway Torque. Breakaway torque, with the turbopump conditioned for start, shall not exceed TBD in-lb. A correlation will be developed between ambient and cryogenic conditions.

3.1.1.14 Functional Interface Requirements. The turbopump shall be designed to perform within specification while being influenced by the in-tolerance performance of the following interfacing components. The tolerances include the effects of items 1 (except temperature profile), 2, 3, 4 and 5.

1. Hot Gas Manifold and Fuel Preburner (Includes Combustion Gas Quality, Pressure, and Temperature Profile)
2. Low Pressure Fuel Turbopump Discharge Duct (Includes Propellant Delivery Quality and Pressure)
3. High Pressure Fuel Turbopump Discharge Duct
4. Accelerometers
5. Speed Pickup
6. Thrust Oscillations

3.1.2 HPFTP Hardware Characteristics. The HPFTP, when applied to the SSME engine system shall meet as a minimum, the hardware performance characteristics listed below.

3.1.2.1 Detail Parts

3.1.2.1.1 Main Housings

3.1.2.1.1.1 The main housings shall be designed to limit membrane stresses below yield stress (0.2%) at a pressure of 1.2 X limit pressure condition encountered at 109% RPL plus tolerance additions.

3.1.2.1.1.2 The main housings shall be designed to withstand rupture at a pressure 1.5 X limit pressure condition encountered at 109% RPL plus tolerance additions. Calculations assume maximum operating temperature.

3.1.2.1.1.3 The housing shall demonstrate a resonant vibratory frequency margin $\geq$ 10% for critical excitations that may be encountered at steady state operating points over the operating range of 65% RPL to 109% RPL. The critical excitation sources include but are not limited to blade passing frequencies of the pump impeller and up to 4E of the rotor.

3.1.2.1.1.4 Main housings material characteristics shall not be affected through election of nonmechanical fabrication techniques (ECM/EDM).

3.1.2.1.2 *Internal Pump Housings/Diffusers*

3.1.2.1.2.1 The internal housings shall be designed to limit membrane stresses below yield stress (0.2%) at pressure of 1.2 X limit pressure condition encountered at 109% RPL plus tolerance additions.

3.1.2.1.2.2 The internal housings shall be designed to withstand rupture at a pressure 1.5 X limit pressure condition encountered at 109% RPL plus tolerance additions. Calculations assume maximum operating temperature.

3.1.2.1.2.3 The internal housing shall demonstrate a resonant vibratory frequency margin $\geq$ 10% for critical excitations that may be encountered at steady-state operating points over the operating range of 65% RPL to 109% RPL. The critical excitation sources include but are not limited to blade passing frequencies of the pump impellers and up to 4E of the rotor.

3.1.2.1.2.4 Internal housings material characteristics shall not be affected through election of nonmechanical fabrication techniques (ECM/EDM).

3.1.2.1.3 *Impellers*

3.1.2.1.3.1 The impeller design shall insure no plastic deformation when operated at the turbopump maximum predicted rotor speed at 109% RPL.

3.1.2.1.3.2 The impeller design shall provide a minimum 22% speed margin for burst, based on a maximum operational speed at 109% RPL plus tolerance additions.

3.1.2.1.3.3 The impeller design shall demonstrate a resonant vibratory frequency margin of $\geq$ 10% for critical excitations that may be encountered at steady-state operating points over the operating range of 65% RPL to 109% RPL. No diametrals are allowed in the operating range thru at least 12E. Critical excitations are:

1. Low rotor orders; 1E, 2E, 3E, 4E
2. Volute collector passing at primary and second order
3. Upstream (inlet) struts passing frequency at primary and second order
4. Difference between upstream and downstream passing characteristics at primary order, e.g. exit passages, such as the impeller discharge collectors.

The impellers shall demonstrate less than .005 oz in. unbalance when supported on an arbor at its mating surfaces with the shaft end rotated at 1500 rpm.

3.1.2.1.3.4 Impeller material surface characteristics shall not be affected through use of nonmechanical fabrication techniques (ECM/EDM).

3.1.2.1.4 Pump Section Ball Bearing

3.1.2.1.4.1 The single row ball bearing shall provide a B1 life of not less than 7.5 hours. Bearing load capacity and coolant flow rates will be determined analytically and verified by testing at conditions simulating turbopump operation up to 109% RPL.

3.1.2.1.4.2 Effectiveness of the solid film lubricant transfer will be demonstrated in rig testing at the turbopump design operating speed and load of 109% RPL and for calculated Hertz contact stresses above 300,000 psi.

3.1.2.1.4.3 Bearing heat generation at the turbopump operating loads and speeds (up to 109% RPL) shall not adversely affect the bearings internal radial clearance.

3.1.2.1.5 Turbine Section Roller Bearing

3.1.2.1.5.1 The 360 degree preloaded roller bearing shall demonstrate a B1 bearing life of 7.5 hours. Bearing load capacity and coolant flow rates will be determined analytically and verified by testing at conditions simulating turbopump operation up to 109% RPL.

3.1.2.1.5.2 Effectiveness of the solid film lubricant transfer will be demonstrated in rig testing at the turbopump design operating speed and load of 109% RPL and for calculated Hertz contact stresses above 300,000 psi.

3.1.2.1.5.3 Bearing heat generation at the turbopump operating loads and speeds (up to 109% RPL) shall not adversely affect the bearings internal radial clearance.

3.1.2.1.6 Lift Off Seal

3.1.2.1.6.1 The lift off seal static helium leakage using dry ambient temperatures helium gas MIL-P-27407 shall not exceed 300 scim at a differential pressure of 40 psig applied to the high pressure side of the seal.

3.1.2.1.6.2 The seal shall lift off (sudden increase in leakage) when the high pressure is increased to 100 psig maximum at ambient temperature.

3.1.2.1.6.3 The lift off seal design flow with 37°R liquid hydrogen at 240 psi differential pressure and 7000 rpm shaft speed is 4.5 lb/sec minimum.

3.1.2.1.6.4 The seal shall reseat (sudden decrease in leakage) when the high pressure is decreased to 50 psig at ambient temperature.

3.1.2.1.6.5 The lift off seal will be designed for a Low Cycle Fatigue (LCF) capability of four (4) times service life.

3.1.2.1.6.6 The lift off seal design will include a vibratory resonant frequency margin of ≥ 10% from critical excitations that may be encountered at steady-state operating points in the engine operating range from 65% to 109% RPL. The lift-off seal design will provide wear resistance to assure adequate wear capability over the period between overhauls.

The critical excitations are:
1E, 2E, 3E and 4E

3.1.2.1.7 Turbine Disk/Shaft

3.1.2.1.7.1 The turbine disk/shaft design will insure no plastic deformation of rim or bore features when operated to the turbopump maximum rotor speed at 109% RPL plus tolerance additions, with all blade pull loads included.

3.1.2.1.7.2 The turbine disk/shaft design will provide a minimum 22% speed margin for burst; based on a maximum operational speed at 109% RPL plus tolerance additions. All blade pull loads will be included.

3.1.2.1.7.3 The turbine disk/shaft shall demonstrate a vibratory resonant frequency margin of ≥ 10% for low rotor order excitations of 1E, 2E, 3E, and 4E at steady-state operating points over the engine range from 65% to 109% RPL. No diametrals are allowed in the operating range thru at least 12E.

3.1.2.1.7.4 The turbine disk/shaft will be designed for a Low Cycle Fatigue (LCF) capability of four (4) times service life and infinite HCF life. The turbine disk/shaft shall demonstrate less than .005 oz in. unbalance when supported at the bearing locations and rotated at 1000 rpm.

3.1.2.1.8 Turbine Blade

3.1.2.1.8.1 All blade designs will include a vibratory resonant frequency margin of ≥ 10% from critical excitations that may be encountered at steady-state operating points in the engine range from 65% to 109% RPL.

Critical excitations include, but are not limited to:

1. Low rotor orders i.e., 1E, 2E, 3E, 4E.
2. Differences between upstream and downstream stator counts.
3. Differences between the two upstream stator counts.

4. Upstream and downstream vane passing orders.

5. Number of immediate upstream or downstream struts at primary order and twice primary order.

6. Number of upstream struts one stage removed at primary order.

7. Stationary probe instrumentation where the excitation order is determined by Fourier Series Analysis of the probe spacing.

8. Number of blade outer gas seal segments/slots.

3.1.2.1.8.2 All blades will be designed for a Low Cycle Fatigue (LCF) capability for four (4) times the service life and infinite HCF life.

3.1.2.1.9 Turbine Vanes

3.1.2.1.9.1 All turbine vanes shall have no chordwise and spanwise vibratory bending resonances within ten (10) percent of any critical excitations which occur at sustained turbopump speeds from 65% to 109% RPL.

Critical excitations include but are not limited to:

1. Low rotor orders 1E, 2E, 3E and 4E
2. Upstream and downstream blade passing
3. Primary preburner instabilities - 1st longitudinal, 3rd tangential
4. Vortex shedding excitation

3.1.2.1.9.2 All turbine vane platforms shall have no vibratory resonances within ten (10) percent of the upstream and downstream blade passing frequencies at sustained turbopump speeds from 65% to 109% RPL.

3.1.2.1.9.3 All vanes will be designed for a Low Cycle Fatigue (LCF) capability of four (4) times service life and infinite HCF life.

3.1.2.1.10 Turbine Inlet Duct

3.1.2.1.10.1 The turbine inlet duct shall be designed to limit membrane stresses below yield stress (0.2%) at a pressure of 1.2 X limit pressure condition encountered at 109% RPL plus tolerance additions.

3.1.2.1.10.2 The turbine inlet duct shall be designed to withstand rupture at a pressure of 1.5 X limit pressure condition encountered at 109% RPL plus tolerance additions. Calculations assume maximum operating temperature.

3.1.2.1.10.3 The turbine inlet duct design will have a vibratory resonant frequency margin of $\geq$ 10% from critical excitations that may be encountered at conditions of steady state operation from 65% to 109% RPL.

Critical frequencies include but are not limited to:

1. Low rotor orders 1E, 2E, 3E and 4E

2. Downstream blade passing (1st stage only)
3. Primary preburner instabilities
4. Vortex shedding

3.1.2.1.10.4 The turbine inlet duct will be designed for a Low Cycle Fatigue (LCF) capability of four (4) times service life and infinite HCF life.

3.1.2.1.11 Turbine Turnaround Duct

3.1.2.1.11.1 The turbine turnaround duct shall be designed to limit membrane stresses below yield stress (0.2%) at a pressure of 1.2 X limit pressure condition encountered at 109% RPL plus tolerance additions.

3.1.2.1.11.2 The turbine turnaround duct shall be designed to withstand rupture at a pressure of 1.5 X limit pressure condition encountered at 109% RPL plus tolerance additions. Calculations assume maximum operating temperature.

3.1.2.1.11.3 The turbine turnaround duct design will have a vibratory resonant frequency margin of $\geq$ 10% from critical excitations that may be encountered at conditions of steady state operation from 65% to 109% RPL.

Critical frequencies include but are not limited to:

1. Low rotor orders 1E, 2E, 3E and 4E
2. Upstream blade passing (2nd stage only)
3. Primary preburner instabilities
4. Vortex shedding excitation

3.1.2.1.11.4 The turbine turnaround duct will be designed for a Low Cycle Fatigue (LCF) capability of four (4) times service life and infinite HCF life.

3.1.2.2 Subassembly

3.1.2.2.1 Pump Section Ball Bearing Support System

3.1.2.2.1.1 The combined rotor support system elements of the ball bearing, support housing, and main housing shall exhibit a stiffness (springrate) of not less than 0.5 X 10^6 lb/in.

3.1.2.2.2 Turbine Section Roller Bearing Support System

3.1.2.2.2.1 The combined rotor support system elements of outer race, and main housing shall exhibit a stiffness (springrate) of not less than 3.0 X 10^6 lb/in.

3.1.2.2.3 HPFTP Rotor Assembly

3.1.2.2.3.1 The rotor assembly share exhibit no fundamental bending modes in the operating range from zero rpm to 109% RPL plus tolerance additions.

3.1.2.2.3.2 The rotor assembly shall demonstrate less than .005 oz in. unbalance when supported at the bearing locations and rotated at 1500 rpm.

3.1.2.2.4 Turbine Gas Path (Inlet Duct Through Turnaround and Diffuser Duct)

3.1.2.2.4.1 The turbine gas path shall be designed to preclude flow discrepancies which degrade turbine performance or life. Flow discrepancies include adverse profiles, separation, wakes, and adverse gradients of pressure or velocity. Turbine gas path shall not contribute to an adverse circumferential pressure profile in the HGM collector exceeding that specified in the ICD.

3.1.2.2.4.2- The turbine gaspath airfoils shall be designed to be resistant to Foreign Object Damage (FOD) from debris liberated upstream of the turbine interface.

3.1.2.2.5 Impeller Inlet Flowpath

3.1.2.2.5.1 The impeller inlet flowpath design shall preclude flow discrepancies with degraded pump performance, cavitation margin, or hardware durability. Flow discrepancies include adverse profiles, separation, wakes, and adverse gradients or pressure or velocity.

3.1.2.2.6 Turbine Inlet Bellows Shield and Bellows Assembly

3.1.2.2.6.1 The turbine inlet bellows shield and bellows assembly shall have no resonant vibratory responses within ten (10) percent of any critical excitations which occur at sustained turbopump operating conditions of 65% RPL to 109% RPL.

Critical excitations include but are not limited to:

1. Rotor orders 1E, 2E, 3E and 4E
2. Primary preburner instabilities

3.1.2.2.7 Damper Seal

3.1.2.2.7.1 The damper seal shall provide optimum damping effectiveness.

3.1.2.3 Component Design Requirements

3.1.2.3.1 Pump Performance

3.1.2.3.1.1 The pump shall operate with less than 3% loss in head rise and shall deliver liquid hydrogen at the flowrates and pressures required for all inlet conditions provided by the engine low pressure system within the ICD limits for stable operation between 65% RPL and 109% RPL. The limits of stable operation will be defined for pump operation between 65% and 50% RPL.

3.1.2.3.2 Turbopump Rotordynamic Stability

3.1.2.3.2.1 Nonsynchronous Rotor Whirl. The turbopump will operate over the range of speed from start to 109% RPL with a 20 percent speed margin with no occurrence of discrete subsynchronous rotor whirl above the noise level.

3.1.2.3.2.2 Rotor Vibration. The turbopump will operate over the range of speed from start to 109% RPL with a twenty (20) percent speed margin with no occurrence of detrimental rotor vibratory modes.

3.1.2.3.3 Turbopump Axial Thrust Balance

3.1.2.3.3.1 The turbopump shall provide adequate internal rotor axial thrust balance capability to preclude life degradation of the bearings and bearing support system and other turbopump components. This capacity shall encompass all operating conditions, both transient and steady-state, from start to 109% RPL including shutdown.

3.1.2.3.4 Turbopump Side Loads

3.1.2.3.4.1 The turbopump side loads shall be minimized by design considerations to reduce hydrodynamic and aerodynamic radial load effects. Areas of attention are:

a. Pump inlet flow path geometry
b. Centrifugal pump collector and discharge geometries
c. Pump splitter and vane geometries.
d. Turbine exit diffuser strut geometry
e. Turbine turnaround duct geometry

3.2 Maintainability, Reliability, Safety, and Quality

3.2.1 Maintainability. The high-pressure fuel turbopump shall be designed to meet the CEI Specification.

3.2.1.1 Interchangeability and Replaceability

3.2.1.1.1 Physical Interchangeability. The turbopump and its components having the same part number shall be interchangeable with respect to installation, except that matched parts or selective fits will be permitted when identified to the procuring activity. Individual components shall be configured for installation in only one orientation.

3.2.1.1.2 Functional Interchangeability. The turbopump shall be designed to be capable of replacement without requiring an engine recalibration firing.

3.2.1.1.3 Manufacturing Processes. The turbopumps and components used for verification testing shall meet the requirements of FR-19673-2 (Materials Control Plan) and FR-19685-1 (Manufacturing Plan) and shall be manufactured using controls, procedures, and facilities to be employed for the manufacture of deliverable turbopumps and components.

3.2.1.2 *Identification and Marking*

3.2.1.2.1 *Turbopump.* The turbopump shall be clearly marked per CEI CP 11370 as follows:

Turbopump, Liquid Hydrogen Propellant
Government Model Designation ____________________
Model Specification No. ____________________
Serial No. ____________________
Manufacturer's Part No. ____________________
Contract or Order No. ____________________
Manufacturer's Name or Trademark, U.S. ____________
Manufacturer's Vendor Code No. ____________________

3.2.1.2.2 *Marking of Connections.* The turbopump shall be permanently marked to indicate all connections shown on the installation drawing for instrumentation, propellant, and other fluid connections. All fluid lines shall be marked in accordance with Drawing MIL-STD-1247.

3.2.1.2.3 *Packaging Requirements.* Packing, packaging, identification and marking and preparation for shipment of materials, components and end items shall be in accordance with NHB 6000.1.

3.2.2 Reliability. The HPFTP shall be designed to meet the reliability program plan.

3.2.3 Safety. The HPFTP shall be designed to meet the safety program plan.

3.2.4 Quality Assurance. The turbopump assembly shall be designed such that materials, fabrication processes, cleanliness controls, and tests may be inspected, verified, and/or controlled in accordance with the Quality Program Plan.

3.2.5 Physical Characteristics. The mass characteristics, including wet and dry weight, center of gravity, and rotor polar moments of inertia of the turbopump shall not exceed those specified in ICD CP 11372. The turbopump static and operating envelopes shall be as specified in ICD CP 11372.

3.2.6 Inspection. The turbopump design shall allow for 100% external visual inspection for damage and leakage, and for internal borescope inspection to assess the condition of all bearings, turbine inlet and TAD, first stage blades and vanes and second stage blades. Borescope inspection of the turbine inlet and first stage blades and vanes will require access through the hot gas manifold.

3.2.7 Checkout and Monitor. No special automatic checkout provisions are required in the design.

3.2.8 Service. No special service requirements are permitted in the turbopump design over its useful life.

3.2.9 Access. The turbopump design shall not restrict access to interface hardware attach points.

The turbopump design shall include access for inspection of potential external leak points. A 360° access to separable joint external surfaces (as installed) must be provided for application of leak detecting devices.

The turbopump design shall include access for manual rotation of the turbopump rotor without removing propellant ducts.

3.2.10 Handling. The turbopump design shall include attach points for handling of the turbopump during replacement while the engine is installed in the vehicle (vertical or horizontal attitude) and in government test facility with modified or existing GSE.

3.2.11 Repair. The turbopump is a depot repair item. No special repair features are required in the turbopump design.

3.3 Environments.

3.3.1 Ambient, Storage, and Exposure. The high pressure fuel turbopump shall be designed to perform under the environmental conditions specified in CEI Specification.

3.3.2 Acceleration and Ground Handling. The high pressure fuel turbopump shall be designed for flight vibrations and loads as specified in CEI and ICD Specifications.

3.3.3 Thermal. The high-pressure fuel turbopump thermal protection system shall utilize materials which have properties as specified in the CEI Specification.

3.3.4 Vibration, Shock, and Acoustic Environment. The high pressure fuel turbopump shall be capable of withstanding the vibration, shock, and acoustic load requirements specified in CEI Specification.

3.3.5 Corrosion. Whenever dissimilar metals are in direct contact or environmental conditions allow a galvanic cell to exist, methods of controlling electrolytic corrosion shall be used. Environmental conditions may include test condition, inspection, fabrication, atmospheric exposure, etc. Protective finishes shall be selected in accordance with MSFC-SPEC-250.

The turbopump and its components shall be designed in accordance with MSFC-SPEC-522A to prevent stress corrosion failures. Metallic materials not listed in Table I of MSFC-SPEC-522A or non-"A" rated in MSFC-SPEC-527 shall not be used unless authorized by Material Usage Agreement (MUA - MSFC Form 551).

3.3.6 Contamination. The use of materials, design configurations, etc., which generate contamination shall be minimized. Cored passages, where either the coring material or the casting material can generate or become contamination sources, will be verified as free from contamination by suitable NDT techniques. All drilled or bored passages shall be deburred. A Contamination Control Plan will be provided.

3.3.7 Moisture. Moisture shall be considered per MIL-T-152B in the design of the turbopump. The turbopump shall be designed to minimize the retention of condensed moisture in traps and to permit the removal of condensed moisture by post shutdown purging with dry nitrogen.

3.3.8 Fungus Resistance. The use of fungus nutrient materials shall be prohibited.

3.4 Design Criteria. The high pressure fuel turbopump shall be designed to demonstrate that the design criteria of CEI Specification can be met at the end of the specified service life.

3.4.1 Structural Criteria

3.4.1.1 Safety Factor Criteria. The turbopump components shall be designed to provide the following minimum factors of safety (per MSFC-STD-505A).

Yield Factor of Safety - 1.10 X limit load
Ultimate Factor of Safety - 1.40 X limit load

The above factors of safety shall apply under the most critical expected conditions of operation, including FPL and the combination of all vibratory, thermal, tolerance buildup and surging effects. Local yielding is allowed provided it is limited and is not detrimental to proper operation. The safety factors specified shall be met at the end of the service life. Power level 2σ tolerance additions include:

1. Deteriorated performance
2. Manufacturing tolerances
3. Run/run variation
4. Control tolerances
5. Inlet conditions (propellants)

3.4.1.2 Pressure Vessel Structural Criteria.

3.4.1.2.1 Limit Load Conditions. The turbopump structural design will be based upon the maximum operating temperatures, pressures and speeds expected during flight or static firing operation. Hereafter referred to as limit conditions.

3.4.1.2.2 Proof Criteria

Proof criteria: Membrane stress < 0.2% yield at 1.2 X limit load or based on fracture mechanics proof test logic (Ref. ATD Fracture Control Plan), whichever is greater.

3.4.1.2.3 Burst Criteria

Burst criteria: No failure at 1.5 X limit pressure at maximum operating temperature.

3.4.1.3 Fatigue Criteria. All structural components of the turbopump assembly shall be designed to the following factors:

1. Low cycle fatigue: service life X 4 (mission cycles) based on minimum properties
2. High cycle fatigue: Infinite life (1 X 10^8 cycles) based on minimum properties

3.4.1.4 *Fracture Control Criteria*. The turbopump fracture control criteria will be defined by P&W Fracture Control Plan FR19793-1.

3.5 P&W/Military Specifications and Standards

3.5.1 P&W/Military Specifications and Standards. The HPFTP Specifications and Standards are listed in Section II, Applicable Documents, of this DVS. Individual Specifications and Standards are referred to throughout the DVS text.

3.5.2 Standards. Standard design practices shall be used in the design of the HPFTP.

3.5.2.1 *Parts.* MC, MS, AN or MIL standard parts shall be used wherever they are suitable for the purpose, and shall be identified by their standard part numbers.

3.5.2.2 *Design.* MC, MS, or NAS design standards shall be used wherever applicable.

3.5.2.3 *Threads.* Conventional straight screw threads shall conform to the requirements of MIL-S-8879. Class 3A or 3B, except that the use of MIL-S-7742 threads shall be optional on:

a. Screws less than 0.164 inch dia.

b. Interference fits such as the installation end of studs or the external threads of inserts, and their tapped holes.

c. Fluid fittings or other nonstructural parts where no Military Services or NASA standard drawings exist for parts with the MIL-S-8879 thread form.

For critical fastener applications, where fastener stress greater than 160,000 psi, and particularly where fatigue is a problem, the threads shall be rolled after heat treatment.

3.5.2.4 *Parts List.* The parts list for the turbopump shall reflect the part number called out by the drawings that successfully completes preliminary and/or final certification and shall constitute the approved list. Changes to the approved parts list shall be maintained by means of engineering changes. The parts list will be used to preclude obsolete parts from getting into the turbopump according to the Configuration Management Plan.

3.5.2.5 *Dimensional Units.* Unless otherwise specified, all dimensional units shall be expressed in the English system of units.

3.5.2.6 *Material Properties and Design Allowables.* The HPFTP shall be designed employing material properties based on MIL-HDBK-5 ("B" Basis) or minus 3σ basis or other basis or sources to be authorized by the procuring activity as specified in the Materials Control Plan (DR SE09).

3.5.2.7 *Materials.* Materials used in the manufacture of the HPFTP and accessories shall be of high quality, suitable for the purpose, and shall conform to the requirements as specified in the Materials Control Plan (FR19673-2) and shall be capable of fabrication per the design requirements.

3.5.2.8 Processes. Processes used in the manufacture of the HPFTP shall be of high quality, suitable for the purpose, and shall conform to the requirements as specified in the Materials Control Plan (FR-19673-2) and the Manufacturing Plan (FR-19685-1). Contractor specifications that are used for processes shall be released to the Government concurrent with release of the applicable drawing. The use of non-Government specifications shall not constitute waiver of Government inspection..

3.5.2.9 Welding Process. Fusion welds, if incorporated, shall be made in accordance with requirements. Welding processes shall meet the requirements of PWA 16, MSFC-SPEC-560, MSFC-STD-655, and MSFC requirements to be incorporated as additional notes on the engineering drawing as specified in the Materials Control Plan (FR-19673-2).

3.5.2.10 Parts and Materials Program. Maximum use shall be made of parts and components which have been qualified as meeting the performance, reliability and quality requirements of the contract. The design shall include application of any preferred parts cited in the contract or required to be established by P&W to eliminate from the design, parts known to be inadequate, and to aid in planning, testing and screening of parts and components.

3.5.2.11 *Flammability, LOX/GOX and Propellant Compatibility.* As a general requirement for all materials, the contractor shall obtain data on analyses as necessary to meet the requirements of NASA document NHB 8060.1B "Flammability, Odor and Offgassing Requirements and Test Procedures for Materials in Environments which Support Combustion". Materials not meeting the requirements of NHB 8060.1B for the worst case environment, (for example, pressure, oxygen concentration, temperature, etc.) shall require the approval of NASA prior to incorporation in the design. Material exposed to high pressure LOX/GOX shall meet the requirements of NHB 8060.1B and NAS 1113.

3.5.2.12 *Materials Selection List.* An ATD Material Selection List (MSL) incorporating data form SMFC-HDBK-527, in a listing of specification, acceptable environment and additional criteria, referenced to the material shall be provided, with the final MSL subject to NASA approval. Additions of materials or process specifications to the approved MSL will require submission of a Material Usage Agreement (MUA) to NASA for review and approval.

3.5.2.13 *Hydrogen Embrittlement.* The mechanical properties of ATD materials operating in a hydrogen or hydrogen plus steam environment will be determined by laboratory testing at P&W or MSFC. Tests will be conducted in simulated operating environments of the material/component using standard test specimen geometries. Sufficient data shall be generated to provide substantitated statistical analysis. Appendix A-4 of the Materials Control Plan contains a minimum test plan for each material Subsequent test results will be included in the SSME/ATD Materials Manual. Materials exposed to hydrogen which are not rated "A" as defined in MSFC-HDBK-527, at the use temperature and pressure, shall be submitted to NASA for review and approval via MUA.

3.5.2.14 *Braze Processes.* Braze processes are required to meet the requirements of ATD Materials Control Plan. Brazed joints shall be designed for shear loading only and shall not be used in any structure requiring strength in tension. Each braze joint configuration shall be mechanically tested to determine mechanical properties of the braze joint as defined in the braze characterization plan of the ATD Materials Control Plan, Section 3.4.3 Each component braze joint shall be non-destructively tested to determine the integrity of the braze joint.

3.6 Failure Mode, Effect, and Criticality Analysis

3.6.1 Failure Mode, Effect, and Criticality Analysis. A FMEA shall be furnished for each part of the HPFTP assembly in order to produce a FMECA for the engine system. Failsafe design criteria shall be determined to satisfy the CEI Specification.

3.6.2 Safety. The high pressure fuel turbopump shall be designed to minimize hazards which could result in injury or loss of personnel, equipment, or property within the constraints of operational effectiveness, time, and cost during all phases of the program.

3.6.3 Failsafe Design. In the event of a single failure in any external functional component, the turbopump shall be capable of being shutdown in a manner which will be self-contained and minimize damage to neighboring parts. In addition, the turbopump shall incorporate a speed monitoring transducer so that in the event of a turbopump failure, the engine may be shutdown in a manner that will be self-contained and will minimize damage to neighboring systems.

3.7 System and Design Analysis Results

3.7.1 Design Verification Test Plan. Verification test plans for all the following design procedures requiring significant test activity shall be prepared and submitted in accordance with data requirement SE07:

a. Bearing Rig Tests

b. Lift-off Seal Tests

c. All E-8 Component Tests

d. TTB and NSTL Engine Tests

Verification procedures for which Design Verification Test Plans shall be submitted are identified in Section 4.0, Design Verification Provisions.

3.7.2 DVS Status Reports. A report of the status of progress and completion on design verification shall be provided in accordance with data requirement SE11.

3.7.3 Verification Complete Package (VCP). A VCP shall be submitted in accordance with data requirement SE12 to document the completion with supporting rationale for each DVS requirement. For requirements accomplished by analysis, the VCP shall contain a summary of analysis activity and reference to the P&W Design Substantiation Memo (DSM).

SECTION 4
DESIGN VERIFICATION PROVISIONS

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4.0 DESIGN VERIFICATION PROVISIONS

4.1 Verification Analysis and Testing. The Design Verification process of verifying the design at the lowest possible test level will be incorporated. Each test will be used to verify the analytical prediction as well as the acceptability of the design. The interaction between the design, analysis, and test necessary to complete each level is depicted in Figure IV-1. Through this interactive process, the confidence in the design is maximized at its earliest time and lowest level while the risk of not meeting the design requirements is minimized in each successive level. Utilizing this process not only minimizes the impact of design problems, but the burden of detecting and diagnosing design problems and then substantiating a redesign at the engine level will be virtually eliminated.

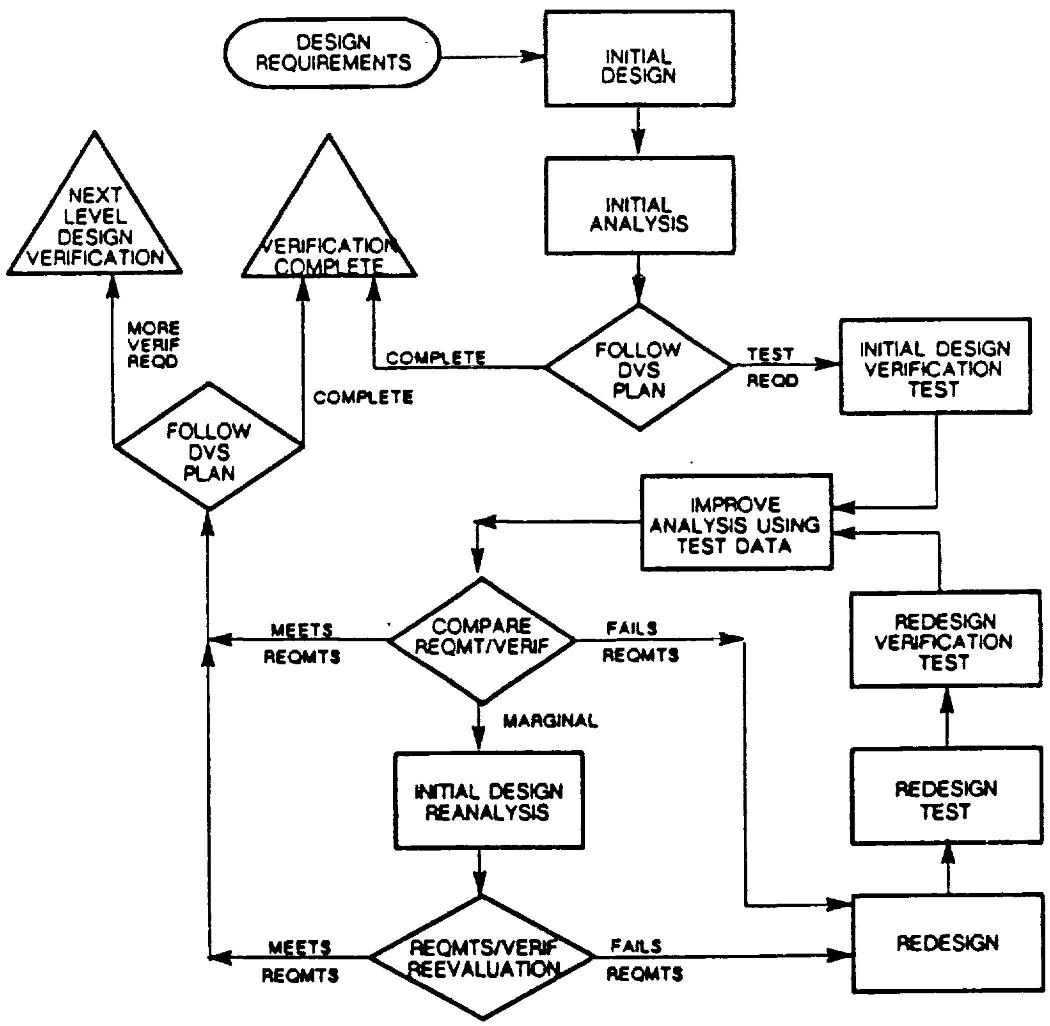

Figure IV-1 *Design Verification and Substantiation System Flow Chart*

4.1.1 Functional Characteristics

4.1.1.1 Functional Performance

4.1.1.1.1 Requirements. Section 3 states that the turbopump shall meet the requirements of the engine start, mainstage, throttling and shutdown requirements.

4.1.1.1.2 Analytical Correlation. The E-8 test data will be analyzed to characterize the turbopump. This characterization will be implemented in the ATD-DTM and ATD-PBM computer models of the SSME. These models will be exercised to ensure that the engine will operate acceptably during engine start, mainstage, throttling and shutdown as required in the ICD.

The ability to meet these requirements will be the basis for verifying the ability of the turbopump to perform within specification while being influenced by the performance at the functional interfaces.

4.1.2 Verification Analysis. Preliminary analyses planned are described below. This section will be further defined and updated by DVS document revisions as HPFTP design requirements and predicted environments are defined.

4.1.2.1 Turbopump Performance Analysis. Performance analyses will be conducted to verify that the ATD turbopump will meet the following requirements:

a. Be compatible with SSME Phase II and II+ performance requirements as defined by the CEI (CP11370) and ICD (CP11372)

b. Minimize interface fluid deviations from the current SSME Data Base for 65% RPL to 109% RPL

c. Minimize changes in controller gains to meet stability requirements with the ATD turbopump installed.

Turbopump performance analysis tools, input parameters and analysis results are as follows.

The SSME Power Balance Model (ATD-PBM-1187) and SSME Digital Transient Model (ATD-DTM-587) are used for these verification analyses. Design performance characteristics of the alternate turbopumps are input into these engine simulations and engine operation during start, mainstage, and shutdown are predicted. These analyses will be updated following turbopump assembly tests on E-8 test facility (paragraph 4.1.3.3.2) by using experimental performance data as input to the models and repeating the verification analyses. The analyses will, again, be updated following engine level testing at MSFC (paragraph 4.1.3.4.2) to verify compatibility with certification and flight engine configurations.

Verification Complete Criteria. Verification will be considered complete when the above analyses have been completed, when it has been established that the worst operating conditions have been considered, and when the above requirements have been met.

4.1.2.2 Mechanical Design Features Analysis. The design requirements for the mechanical and functional interchangeability and replaceability with the SSME Phase II and Phase II+ HPFTP as a line replaceable unit (LRU) will be verified by analysis and testing.

Verification Complete Criteria. Verification will be considered complete when the following analyses and tests have been successfully completed.

a) Mechanical Interchangeability and Replaceability will be analyzed by reviewing and correlating the ATD engineering drawings & specifications with all applicable documents of Section 2 of the DVS. This review and correlation will show that all relevant requirements have been followed and are properly documented and implemented. Dimensional stackup calculations will also be made, where applicable, to ensure that these requirements have been met at the drawing tolerance extremes.

b) Mechanical & Functional Interchangeability will be analyzed by including the effects of temperature, pressure and centrifugal variations on the various dimensional stackups.

c) Functional Interchangeability will be ensured by statistical evaluation of all turbopump performance data obtained from DVS testing, and analysis of that data per Section 4.1.2.1.

d) Mechanical Replaceability will be demonstrated by an early test with mockups showing that the ATD turbopump can be successfully removed and replaced as a Line Replaceable Unit (LRU) as noted in paragraph 4.1.5.1.

4.1.2.3 Pump Hydrodynamics Analysis. Pump hydrodynamics analyses will be conducted to verify that the ATD turbopump will:

a. Improve pump suction performance by optimizing inlet volute flowpath and velocity distributions

b. Reduce the inlet flow coefficient by increasing the impeller inlet area

c. Improve performance by optimizing impeller incidence and blade contours

d. Improve performance by optimizing inlet guide vane incidence and vane shape

e. Reduce leakage by improving the pump seal configuration.

f. Minimize hydrodynamic sideloads.

Pump Hydrodynamics Analysis tools, input parameters, and analysis results are as follows:

a. *Hydrodynamic Meanline Analyses.* As an initial procedure in defining the hydrodynamic design requirements of the turbopumps, prior to detailed indepth analyses, meanline calculations are conducted for each subcomponent of the pump (i.e. inlet and discharge ducts, and impellers). Various empirical models are employed in the analyses to describe overall hydrodynamic parameters for each pump element, including correlations of loss coefficient, fluid deviation angles, cavitation parameters, and basic sizing criteria. The resultant analyses establish the overall inlet and discharge flow conditions for each element, which are subsequently refined and updated based upon detailed internal flow analyses. Predicted parameters from the analyses are compared with experimental test values required to accurately simulate component rig data. Reference paragraph 4.1.3.2.1.1.

b. *Empirical Design Correlations.* Numerous empirical correlations and design criteria have been formulated at P&W, based upon available experimental data, for hydrodynamic analysis of turbopump components. Included in the above are correlations of loss coefficient and fluid deviation angle for impellers and vane cascades, cavitation criteria, hydrodynamic loading limits, etc. The empirical models provide a basis for modifying theoretical analyses to account for the influence of viscous and secondary flow effects on pump performance and stability. Analytical predictions derived from the correlations are compared to experimental data from component rig tests where available. Reference paragraph 4.1.3.2.1.1.

c. *3-D Potential Flow Analysis (VSAERO Code).* VSAERO is a potential flow code, based on the panel method, capable of simulating internal subsonic flows for arbitrary 3D geometries. The inviscid 3D solution of internal velocity and pressure distributions provides a versatile tool for hydrodynamic analyses of the turbopump components and subsequent comparison with experimental data for design evaluation. Reference paragraph 4.1.3.2.1.1.

d. *Quasi 3-D Inviscid Flow Euler Analysis.* The P&W quasi 3-D Euler code is a versatile analytical tool for internal flow analysis of centrifugal, mixed-flow, and axial impellers and vanes. The simultaneous solution of radial equilibrium continuity, intrablade, and energy equations provides a three-dimensional definition of velocity and pressure distributions throughout the internal flowfield. Loss and fluid deviation coefficients, based on empirical correlations, are applied within the analysis to account for the influence of viscous and secondary flow effects on pump performance and stability. Analytical predictions derived from the program are compared to experimental data from component rig tests where available. Reference paragraph 4.1.3.2.1.1.

e. *NASTAR Analysis (Navier-Stokes)*. The NASTAR code used to model turbopump components is a finite volume Computational Fluid Dynamics (CFD) analysis that numerically solves the 3-D Navier-Stokes equations governing the flowfield. Three dimensional geometry, and inflow conditions such as flowrate and static pressure, are required input. NASTAR output provides a complete 3-D definition of flowfield velocities and pressures for comparison with experimental data from component rig tests. Post processing of variables defines pressure losses, regions of flow separation, and other flow phenomena of interest. Reference paragraph 4.1.3.2.1.1.

Verification Complete Criteria. Verification will be considered complete when the following analyses have been completed, when it has been established that the worst operating conditions have been considered, and when the above requirements have been met.

a. 1-D Meanline Analysis

b. Empirical Design Correlations

c. 3-D Potential Flow Analysis (VSAERO Code)

d. Quasi 3-D Inviscid Flow Euler Analysis

e. 3-D Navier Stokes Solution (NASTAR-F Analysis).

4.1.2.4 Turbine Aerodynamic Design Analysis. Turbine aerodynamic design analyses will be conducted to verify that the ATD turbopump:

a. Turbine design has adequate efficiency over the operating range

b. Turbine design has adequate margin for ease of SSME cycle balancing

c. Turbine exit swirl is optimized to ensure turnaround duct performance.

The turbine aerodynamic design analysis tools, input parameters and analysis results are as follows:

a. Turbine Meanline Design Analysis (TMLD) (Code P774) - Used to calculate design and off design velocity diagrams, gas conditions and airfoil and overall performance estimates. It is also used for calculating turbine power from measured data. The input parameters include flowpath geometry, stage work, reactions and inlet aerodynamic conditions. (Ref. paragraph 4.1.3.1.1)

b. Streamline Flowpath Analysis (SLD) (Code W677) - Used to compute the radial component terms in the flow equation. W677 enables the turbine designer to include radial profiling of flow conditions and angles (controlled vortexing) in order to achieve improved spanwise performance. Other uses include matching analysis data to experimentally measured flow conditions, assessing local blockage effects and establishing axisymmetric boundary conditions. Input parameters include flowpath geometry, inlet aerodynamic conditions such as flow rate, temperature, pressure, and angle.

c. Turbine Three-Dimensional Flow Analysis (V310) - Used in the turbine design process to analyze the complete turbine flowpath. The code is used in an iterative and interactive manner to refine the airfoil and endwall geometries defined in earlier steps. V310 allows the user to input the entire turbine geometry (ie: flowpath and foil definition, including multi-stage geometries and turn-around ducts). Three-dimensional flow analysis shows how the various component geometries interact and the subsequent overall effect of the flow-field. Various grid generators are available for a wide range of geometries.

d. Turbine Airfoil Pressure Distribution Analysis (M905 & T862) - Used to evaluate candidate airfoil geometries, and their associated pressure distributions obtained from the internal T862 deck option. T862 uses an inviscid, transonic, potential flow calculation, with boundary layer options, to predict the foil pressure distribution defined by geometry in M905.

Input Parameters Include - Inlet/exit aerodynamic parameters at a radial location. Chord, L.E. and T.E. foil diameters, and metal angles.

e. Turbine Airfoil Stress Analysis (P824) - Uses the external airfoil definition from M905, internal airfoil definition from durability requirements, and the aerodynamic bending moments from the streamline to calculate net loads and moments acting upon a foil. P824 is used to radially stack and fair the various airfoil sections for complete 3-D airfoil definition.

Input Parameters Include - Foil external and internal geometries, and aerodynamic bending moments.

Verification Complete Criteria. Verification will be considered complete when the following analyses have been completed, when it has been established that the worst operating conditions have been considered, and when the above requirements have been met.

a. Meanline Design Analysis (TMLD) Code P774

b. Streamline Flowpath Analysis (SLD) Code W677

c. 3-D Flow Model of Inlet Struts, Airfoil Rows and Turnaround Duct

d. Airfoil Pressure Distribution Analysis (Codes M905, T862, and V760)

e. Airfoil Stress Analysis (Code P824)

4.1.2.5 *Turbine Airfoil Durability Analysis.* Turbine airfoil durability analyses will be conducted to verify adequate life for the three aspects of airfoil durability.

a. Airfoils have a creep life capability of 4 times the service life at power levels up to 111% RPL

b. Airfoils will have a low cycle fatigue (LCF) capability of 240 cycles at power levels of up to 111% RPL

c. Airfoils will have an infinite (10^8 cycles) HCF life.

The turbine airfoil durability analysis tools, input parameters and analysis results are as follows:

a. Creep Analysis - Creep life is calculated using material minimum property data correlated by using a larson-miller parameter which gives creep life as a function of pull stress and metal temperature. Each airfoil cross section is analyzed using its pull stress and metal temperature. The metal temperatures from ID to OD are obtained using the turbine inlet temperature profile data from instrumented checkout chamber and turbine simulator tests of both the STE and GFE injectors. Verification of creep capability will be made by the creep test described in 4.1.4.4.1.3.

b. LCF Analysis - The LCF analysis of the ATD turbine airfoils is done using a general purpose finite element program (MARC) for both the transient thermal analysis and the strain analysis. Input into the thermal model includes geometry, density, specific heat, conductivity, heat transfer film coefficients, and transient mainstream gas temperature. The heat transfer film coefficient correlations are obtained from empirical heat transfer correlations which use the fluid properties of hydrogen and steam. Input into the strain model include goemetry, metal temperatures from thermal analysis, pull load, bending moments, density, coefficient of thermal expansion, poisson's ratio, and modulus of elasticity.

   The strain from the Marc analysis are converted to LCF capability using an empirical curve derived from the testing at MSFC's thermal cycle rig described in 4.1.4.1.8.3. This empirical curve was derived by combining demonstrated cycles to crack initiation with predicted strains of the rig hardware. The predicted strains were obtained from detailed Marc analyses of rig hardware using measured rig inlet temperature and pressure to determine the rig transient thermal boundary conditions.

   The LCF capability of the ATD airfoils is verified in a progressive fashion as the development program proceeds. Early verification of the thermal shock benefits of a thermally responsive foil design was shown in the MSFC's thermal cycle rig described in 4.1.4.1.8.3. Later testing in this rig verified the thermal shock capability of the vane alloy, PWA 1447, in the H_2/H_2O environment along with additional laboratory material testing. Also later rig testing quantified the effect of other parameters such as surface finish and crystallographic orientation.

The next level of verification is based on the detailed Marc analysis described previously. This analysis includes the centrifugal and bending loads on the airfoil as well as the mainstream hot gas boundary conditions obtained from previous engine measured data.

During the turbopump testing on E-8 test stand (paragraph 4.1.4.3.1.2), the actual airfoil is tested during both transient and steady state operation. The transient turbine inlet hot gas environment is being adjusted to simulate the same thermal shock severity as in the full engine. An optical pyrometer will be used to measure turbine airfoil thermal response during this testing to verify analytical metal temperature predictions and LCF capability of the airfoils. The cyclic capability of the hardware will be assessed by detailed examination after running. Instrumentation in the checkout chamber, turbine simulator rig, and turbopump will allow proper characterization of the environment to identify and correct any situation which deviates from design intent.

Engine level testing (Ref. paragraph 4.1.4.4.1.5) is the final verification. Instrumentation in the technology test bed can be used to further verify the environment and adjustments to the detailed hardware analysis can be made. An optical pyrometer and an ARTS package will be utilized to measure turbine airfoil thermal response and the turbine inlet gas temperature profile, respectively, during engine level testing at NSTL based upon E-8 experience. Further life improvements can then be logically made as required.

c. Airfoil HCF analysis is discussed in Section 4.1.2.9.

Verification Complete Criteria. Verification will be considered complete when the following analyses have been completed, when it has been established that the worst operating conditions have been considered, and when the above requirements have been met.

a. Creep Analysis

b. 3-D MARC Analysis

4.1.2.6 Turbine and Pump Internal Flow Management Analysis. Turbine and pump internal flow management analyses will be conducted to verify that the ATD turbopump turbine

a. Outflow cooling is positive at each interstage location to prevent ingestion of hot flowpath gases

b. Cooling flow parasitic losses are minimized

c. Critical hardware metal temperatures and thermal gradients are controlled

d. Rotor axial thrust balance control is maintained

The turbine and pump internal flow management analysis tools, input parameters and analysis results are as follows:

a. 1-Dimensional Compressible Flow Analysis with orifice/seal empirical loss factors - Used to calculate pressures, temperatures, and flows at numerous time points to define transient conditions of the HPFTP during test and flight. Input parameters include flow and interstage pressures and temperatures. The empirical loss factors of orifices and labyrinth seals will be substantiated by comparing predicted internal pressures, temperatures and flows with those obtained in testing outlined in 4.1.3.2.2, 4.1.3.2.3, 4.1.3.3.2, 4.1.3.3.5.1, 4.1.3.3.6, 4.1.3.3.7, and 4.1.4.1.2.2.

b. Off-Design Temperature/Flow Analysis - Used to define the transient boundary conditions for the 1-D compressible flow and the 3-D Transient Temperature Analysis by using the mission profile, thrust level, flows and mission time and the turbine off-design code. The interstage pressures and temperatures will be substantiated by comparing predicted values with those obtained in testing outlined in 4.1.3.2.2, 4.1.3.2.3, 4.1.3.3.2, 4.1.3.3.5.1, 4.1.3.3.6, 4.1.3.3.7 and 4.1.4.1.2.2

c. Axial Thrust Load Analysis - Used to define the axial thrust load capability utilizing the pressures calculated in the 1-D Compressible Flow analysis and calculated areas. Proximity probes will define the rotor axial position and effect the flows calculated in the 1-D Compressible flow Analysis. Pressures and axial thrust load capability will be substantiated through testing outlined in 4.1.3.2.2, 4.1.3.2.3, 4.1.3.3.2, 4.1.3.3.5.1, 4.1.3.3.6, 4.1.3.3.7 and 4.1.4.1.2.2.

d. 3-Dimensional Transient Temperature Analysis - Used to calculate boundary conditions which controls temperature and thermal gradients. Input parameters include pressures, temperatures, and flow from the 1-D Compressible Flow Analysis. Calculated values will be substantiated through testing outlined in 4.1.3.2.2, 4.1.3.2.3, 4.1.3.3.2, 4.1.3.3.5.1, 4.1.3.3.6, 4.1.3.3.7, and 4.1.4.1.2.2.

Verification Complete Criteria. Verification will be considered complete when the following analyses have been completed, when it has been established that the worst operating conditions have been considered, and when the above requirements have been met.

a. 1-D Compressible Flow Analysis with Orifice/Seal Empirical Loss Factors

b. Off-Design Temperature/Flow Analysis

c. Axial Thrust Load Analysis

d. Heat Transfer Analysis

4.1.2.7 Bearing Systems Analysis. Bearing systems analyses will be conducted to verify that the ATD turbopump meets the following goals.

a. Provide a minimum B1 life of 7.5 hours of operation including 60 missions at power levels up to 109% RPL.

b. Rotordynamic Criteria.

c. Trade studies shall be conducted on the pump ball bearing to optimize bearing performance and preload based on the following requirements:

   - Hertzian stress for effective solid film lubrication
   - Stress-velocity factor to reduce inner race wear
   - Bearing radial stiffness to reduce rotor dynamic loads
   - Ball bearing excursions for cage-jacket riveting and cage strength
   - Bearing spin-to-roll ratio to reduce frictional heat generation
   - Coolant flow analysis

d. Trade studies shall be conducted on the roller bearing to optimize bearing performance based on the following requirements:

   - Negative roller bearing Internal Radial Clearance (IRC) to ensure bearing stability
   - Axial travel limits
   - Crowned rollers to prevent roller edge loading
   - Coolant flow analysis

e. Radial loads from pump (hydraulic) and turbine (aerodynamic) circumferential pressure variations.

The bearing systems analysis tools, input parameters and analysis results are as follows:

a. Jones II and Jones V Ball Bearing Analysis - Used to calculate B1 life, Hertzian contact stresses, Stress-velocity factor, radial stiffnesses, ball excursions, ball path height, and spin to roll ratio. Input parameters include bearing internal geometry, axial load, radial load, misalignments, and speed. The ball bearing design and performance characteristics will be substantiated with the testing outlined in 4.1.4.1.2.2, 4.1.4.1.2.4 and 4.1.4.3.1.4.

b. Jones IV Roller Bearing analysis - Used to calculate B1 life, Hertzian Contact stresses, radial stiffnesses, roller edge loading, and roller loading. Input parameters include bearing internal geometry, roller geometry radial load, misalignments, and speed. The roller bearing design and performance characteristics will be substantiated with the testing outlined in 4.1.4.1.2.2, 4.1.4.1.2.3 and 4.1.4.3.1.4.

c. Shaberth Bearing Frictional Heat Analysis - Used to calculate the frictional component of bearing heat generation for the ball and roller bearings. Input parameters include internal geometry, axial load, radial load, speed, and coefficient of friction. The frictional heating values from the model will be correlated with temperature data obtained from the testing outlined in 4.1.4.1.2.2, 4.1.4.1.2.3, and 4.1.4.3.1.4..

d. Fit Analysis - Used to establish the assembly fits of the bearing stackup and the bearing free state internal clearance needed to provide the desired operating internal clearances. Calculates operating fits, contact pressures, hoop stress levels, and bearing operating internal clearances. Input parameters include bearing internal geometry, shaft and housing dimensions, material properties at operating temperatures, axial pinch loads, and speeds. The models will be correlated from the testing outlined in 4.1.4.1.2.2 , 4.1.4.1.2.3 and 4.1.4.3.1.4 .

e. Skid Analysis - An emperical derived analysis from gas turbine experience used to determine if ball skid occurs. Input parameters include race geometry, radial and axial loads, bearing internal clearances. Visual examination of rig and component tested ball bearings (section 4.1.4.1.2.2 through 4.1.4.1.2.4 and 4.1.4.3.1.4) will determine if skid has occurred.

f. Heat Transfer Analysis - Friction heat generation calculated with Shaberth to be used in conjunction with empirically derived equations for drag and Euler heat generation. Total heat generation used to establish coolant flow requirements and as input to thermal models of the bearing components to calculate bearing component temperatures. Input parameters include bearing geometry, axial load, radial load, coefficient of friction, speed, flowrates, and fluid pressures and temperatures. The models will be correlated with data obtained from testing outlined in 4.1.3.3.4.1, 4.1.4.1.2.2. , 4.1.4.1.2.3 and 4.1.4.3.1.4.

g. Cage Structural Analysis - NASTRAN finite element structural model will be used to predict stresses and thermal contractions of the cage. Input parameters include cage geometry, material properties at operating temperature, operating temperatures, and speed. Cage design will be substantiated with testing outlined in 4.1.4.1.2.2, 4.1.4.1.2.3 and confirmed in component and engine tests (4.1.4.3 and 4.1.4.4).

h. Pump and Turbine Sideload (Radial) Analyses - The loads predicted by hydrodynamic and rotor dynamic analyses will be used to analyze radial overload conditions, testing will be conducted in 4.1.4.1.2.2 , 4.1.4.1.2.3 with radial overloads to verify the bearings can tolerate the increased contact dynamics and heat generation. This analysis will be confirmed by component and engine tests (4.1.4.3 and 4.1.4.4).

Verification Complete Criteria. Verification will be considered complete when the following analyses have been completed, when it has been established that the worst operating conditions have been considered, and when the above requirements have been met.

a. Jones II and Jones V Ball Bearing Analysis

b. Jones IV Roller Bearing Analysis

c. Shaberth Bearing Heat Analysis

d. Fit Analysis

e. Skid Analysis

f. Heat Transfer Analysis

g. Cage Structural Analysis

h. Pump and Turbine Sideload (Radial) Analyses

4.1.2.8 Damper Seal Systems Analysis. An analysis of the damper seal will be conducted to verify that the ATD turbopump damper seal stiffness and seal damping capabilities are optimized for successful rotordynamic characteristics and seal leakage is consistent with bearing coolant flow requirements. Results from test paragraph 4.1.3.2.2 will be used to verify the analytical damper seal coefficient predictions generated from paragraph 4.4.2 analysis and testing. This correlation will then be used to assess turbopump models.

4.1.2.9 Structural Design Analysis. Structural design analyses will be conducted to verify that the ATD turbopump:

a. Has adequate stress/life margins..., i.e., satisfies LCF life, safety factor and fracture mechanics requirements

b. Has proper clearances and tight snap fits throughout the operating speed range

c. Vibratory modes which are detrimental are tuned away from primary excitations.

d. Structural design is based upon the SSME ATD Design Criteria/Guidelines (FTDM 2624) and MSFC-STD-505A.

The Structures Design Analysis tools, input parameters, and analysis results are as follows:

Verification of steady stress and life analysis include verification of both analysis input and output. Input verification includes development of material mechanical properties for use in the analysis and fatigue and fracture properties, which in conjunction with stress predictions resulting from the analysis, are used to predict engine cyclic operational capability. Material property verification is being conducted in the ATD "Materials Control Plan" (FR19673-2).

Other input verification items include environmental loadings experienced by the components throughout the operational cycle (steady state and transient). This includes rotor speeds, pressures, temperatures and interface loadings, including the random vibration levels as defined in the ICD. This input information is obtained through analyses and verified by numerous rig to full engine level tests detailed in Section 4.1.3.

Verification of steady stress analysis results is accomplished through structural testing of individual parts and through measurements made on rig to full engine test programs. Individual part tests include pressure proofing and spin tests, where strain gage surveys are taken as a function of loading; and photoelastic plastic modeling which can determine stresses in local areas where direct measurement is not practical. Details of these part tests are given in section 4.1.4.1. Measurements on rig to full engine will generally be limited to strain gage measurements on outer portions of the housings. Environmental considerations limit making internal measurements. The stress analysis models are utilized to predict stress/strain for each of the verification tests using the appropriate loading and environmental conditions for each. Updates are made to the models as required to assure correlation with the test results. These updated models are then recycled through the engine mission cycle to more accurately predict the operational stress and life characteristics of the components.

The level of complexity involved in the steady stress analysis models used in the verification process is dependent on the complexity of the part geometry and loading. In general, symmetric parts with symmetric loading will only require 2D finite element modeling with limited test verification. Non-symmetric parts with non-symmetric loading require 3D finite element modeling and a more thorough verification measurements process. LCF and fracture mechanics life analysis is employed on all parts regardless of analysis complexity. Life verification is largely dependent on the individual verification of part stress and material fatigue characterization. While fatigue tests of complex parts could be conducted, loadings consistent with engine operation cannot be duplicated and therefore reliability of the detail part test, for demonstrating life in engine operation, is severely compromised. The turbopump 60 mission endurance demonstration test (Section 4.1.4.3.1.2 and 4.1.4.4.1.5) will be the best measurement of fatigue capability.

The Structural Design Analysis Verification process is considered complete when all related structural verification testing has been completed, analysis models are updated to correlate with test data, and the updated stress models are used, along with test verified environmental loadings (thermals, pressures, etc), to evaluate components for engine operating conditions.

The ATD turbopump vibration analysis will be completed with the MacNeal Schwendler Corporation industry standard finite element program, Nastran. The ATD turbopump components; the impellers, the turbines, the ducts and the housings; will be modelled and turbopump operating parameters will be simulated. These parameters include the operating speed, the temperature, the material (reference FR-19673-2) and the hardware mass properties. The Nastran modal analysis solution in conjunction with two and three dimensional modeling will predict each components vibratory characteristics. Fundamental vibratory modes will be tuned from components' primary excitation sources outlined in the design criteria per section 4.1.2.9.d.

Each component's vibration analysis will be substantiated with laboratory testing including a combination of modal testing, holographic testing, SPATE/stresscoat testing, shaker table testing, high cycle fatigue testing or spin pit testing. A summary of this vibration testing is shown in Table IV-3. A brief description of each type of test is listed as follows:

Modal Analysis. Modal analysis tests are conducted to determine experimentally the natural frequencies of a structure. The test is completed by exciting the structure with a sinusoidal excitation with a piezoelectric shaker or wideband impact methods. The test is completed for the engine operating frequency range.

Holographic Testing. Holographic testing includes laser illuminated vibrating surfaces studies with the use of time average holograms. The holograms provide a three dimensional view which can be used to detect mode shapes and vibration amplitudes. The vibration excitation is supplied with a piezoelectric shaker with a frequency range encompasing the engine operating range. The holographic testing incorporates structural fixturing which simulates the turbopump assembly.

SPATE/Stresscoat Testing. SPATE/stresscoat testing are used to determine the dynamic stress distribution of a structure. The stresscoat test consists of covering the test article with a brittle lacquer coating and then vibrating the piece in the primary mode while mounted to a shaker table. The test article is driven hard enough to crack the lacquer coating without damage to the parent material. These crack patterns are then used to help identify high vibratory stress locations for later strain gage work.

The SPATE testing is used to enhance the stresscoat results by providing improved resolution in the high stress areas. Like the stresscoat test, SPATE test is a non-destructive test which uses an infrared sensor to scan the test article while vibrated in the mode of interest via the shaker table. The sensor measures the dynamic thermal strain occurring throughout the test article at the resonant frequency and provides a thermal map of the dynamic behavior. The thermal dissipation during vibration results in thermal gradients and "hot spots" which locate areas of maximum vibratory stress. These results are used in conjunction with the stresscoat patterns to ensure that the dynamic strain gage placement and orientation adequately represents the dynamic behavior of the test article.

High Cycle Fatigue Testing: Component HCF capability will be determined with this test. Initial SPATE / Stressed testing and analyzed predictions are used to locate dynamic strain gages at maximum stress locations. The test article is then vibrated with a piezoelectric shaker with necesary input levels to fatigue the piece after several million vibration cycles at the documented stress level. This procedure is repeated with additional test pieces at various stress levels until an adequate statistical sample has been obtained to establish the component endurance limit or HCF strength and capability of the component. Additional notched specimen and/or component testing will be performed to be representative of foreign object damaged (FOD'd) components.

Spin Rig Testing. Component spin testing will include vibratory strain gage surveys to measure dynamic stresses for the turbopump speed range. The vibratory modes will be excited with piezoelectric crystals or air jets.

Verification Complete Criteria. Verification will be considered complete when the following analyses have been completed, when it has been established that the worst operating conditions have been considered, and when the above requirements have been met.

a. Pressure, Stress, Deflection, and Stiffness Analysis

b. 2-D Nastran Steady Stress and Vibratory Analysis

c. 3-D Nastran Steady Stress and Vibratory Analysis

d. LCF Analysis

e. Fracture Mechanics Analysis

4.1.2.10 Rotor Dynamics Analysis. Rotor dynamics analyses will be conducted to verify that the ATD turbopump

a. Critical speeds are tuned with bearing support stiffness and location to ensure that high energy modes are above 109% RPL plus a 20% speed margin.

b. Has sufficient rotor dynamic stability margin within the turbopump operation range.

c. Improved rotor balancing repeatability is assured by using positive concentricity control, two plane detail/assembly with an in housing check balance as required, to insure an effective low speed balance of rigid body modes.

d. Acceptable rotor dynamic response to ensure adequate bearing life.

e. Has sufficient rotor dynamic margins based on parametric studies of governing parameters.

The rotor dynamics analysis tools and analysis results are as follows:

a. *Critical Speed Analysis.* Rotor and housings are represented by a system of discretized masses connected by massless beams. The masses have both gyroscopic and rotary inertia moments while the beams have both bending and shear flexibilities. Struts/vanes, bearings, bearing supports, interface mounts, etc. are represented by lateral and trunnion springs. Lateral modes or the beam model are solved using the Transfer Matrix Method. This Pratt & Whitney analysis is routinely used to accurately predict the dynamics of various rotor designs.

b. *Forced Response Analysis.* Two Programs are used to calculate the steady state vibratory response (displacement, slope, moment, shear) of the critical speed model due to distributed rotor unbalance or constant forces at specified rotor speeds. The A346 program is based on the Transfer Matrix Method and assumes circular whirl orbits for limited analyses. The ARDS program provides capability for asymmetric support and predicts the non-circular forced response.

c. *Static Deflection Analysis.* Using the same critical speed beam model, the static deflection program predicts the deflected shape and loading due to inertial loading from maneuvers applied steady forces and moments.

d. *Damper Seal Analysis.* A damper seal program is used to define dynamic coefficients of high pressure annular seals. The program is based on analytical-computational methods and is capable of modeling seal geometry flow properties and surface treatments.

e. *Nonlinear Transient Response Analysis.* This program uses model information from the critical speed model to predict the time dependent transient response to a variety of time dependent loadings, including rotor acceleration and deceleration. It is also capable of handling a variety of nonlinear springs.

f. *Stability Analysis.* A finite element based program Analysis of Rotor Dynamics Systems (ARDS) is used to analyze the free and forced response of multi-shaft rotor-bearing systems. Systems with nonlinear interconnection and/or support bearings are analyzed by numerically integrating a reduced set of coupled system equations. ARDS was developed through a NASA funded program at Arizona State University under the direction of Professor H.D. Nelson.

A table of rotor dynamics analyses input parameters and verification test references are as follows:

Analytical Parameters

Analyses	Parameters	Verification Test Reference
Critical Speed	Material Properties	Material Control Plan FR-196773-2
	Rotor Stiffness	Paragraph 4.1.4.2.3.1
	Housing Stiffness	Paragraph 4.1.4.1.1.2
	Rotor Support Stiffness	Paragraph 4.1.4.2.1.1-2
	Damper Seal Stiffness	Paragraph 4.1.3.2.2
	Mass Distribution	

Analyses	Parameters	Verification Test Reference
Forced Response	Material Properties Bearing Spring Rate Housing Stiffness Rotor Support Stiffness Damper Seal Stiffness Housing Dynamics Mass Distribution Damper Seal Damping Rotor/Housing Damping Rotor Unbalance	Material Control Plan FR-196773-2 Paragraph 4.1.4.2.3.1 Paragraph 4.1.4.1.1.2 Paragraph 4.1.4.2.1.1-2 Paragraph 4.1.3.2 Paragraph 4.1.4.1.1.2
Static Deflection	Material Properties Bearing Spring Rate Housing Stiffness Rotor Support Stiffness Mass Distribution	Material Control Plan FR-196773-2 Paragraph 4.1.4.2.3.1 Paragraph 4.1.4.1.1.2 Paragraph 4.1.4.2.1.1-2
Damper Seal/ Lift-Off Seal	Pressure Fluid Properties Geometric Dimensions Tangential Velocity Inlet Loss Surface Roughness	Paragraph 4.1.3.2.2 Paragraph 4.1.3.2.2.1 Paragraph 4.1.3.2.3 Paragraph 4.1.3.2.3.1 Paragraph 4.1.4.1.4 Paragraph 4.1.4.1.4.1 Paragraph 4.1.4.1.4.2 Paragraph 4.1.4.1.4.3
Nonlinear Transient Response	Material Properties Rotor Stiffness Housing Stiffness Rotor Support Stiffness Damper Seal Stiffness Housing Dynamics Mass Distribution Damper Seal Damping Rotor/Housing Damping Rotor Unbalance Bearing Dead Band	Material Control Plan FR-19673-2 Paragraph 4.1.4.2.3.1 Paragraph 4.1.4.1.1.2 Paragraph 4.1.4.2.2.1 Paragraph 4.1.4.2.1.1-2 Paragraph 4.1.3.2.2
Stability	Material Properties Rotor Stiffness Housing Stiffness Rotor Support Stiffness Damper Seal Stiffness Housing Dynamics Mass Distribution Damper Seal Damping Rotor/Housing Damping Rotor Unbalance Bearing Dead Band Turbine Alford's Force Hydrodynamic Impeller Force Component Side Loads	Material Control Plan FR-19673-2 Paragraph 4.1.4.2.3.1 Paragraph 4.1.4.1.1.2 Paragraph 4.1.4.2.2.1 Paragraph 4.1.4.2.1.1-2 Paragraph 4.1.3.2.2

Verification Complete Criteria. Verification will be considered complete when the following analyses have been completed, when it has been established that the worst operating conditions have been considered, and when the above requirements have been met.

a. Critical Speed Analysis
b. Forced Response Analysis
c. Static Deflection Analysis
d. Damper Seal Analysis
e. Nonlinear Transient Response Analysis
f. Stability Analysis
g. Fast Fourier Transform Modal Analysis

4.1.2.11 Turbine Exit Flowpath Analysis. Turbine Exit Flowpath Analyses will be conducted to verify that the ATD turbopump turnaround duct will meet the following requirements.

a. Pressure losses, that can adversely affect the SSME cycle, are minimized
b. Flow separation, which can introduce fluctuating pressures/ buffeting loads to flowpath parts, is eliminated
c. Secondary flows, which can cause flow maldistribution into the SSME main injector, are minimized
d. Minimize the circumferential pressure gradient at turbine discharge

Verification complete criteria and verification methods for the above requirements are as follows:

a. Design Analysis of SSME Baseline

   Analysis of flow area distribution and turn angles and SSME baseline flow path and incorporation of these into the ATD HPFTP exit flow path.

b. TAD/Diffuser Full Scale Flow Models

   Flow visualization and pressure measurement tests will be performed using a transparent full scale models of the turbine turnaround duct. These tests will be conducted at Marshall Space Flight Test Center (MSFC) in the Dynamic Fluid Flow (water) Facility and air facility or an equivalent test stand, ref. para. 4.1.3.2.5.1. Turbine turnaround duct tests will define the flow distribution and patterns, including circumferential variation and verification of strut alignment. Flowpath total pressure loss and static pressure recovery will also be verified.

c. 2-D Axisymmetric Analysis (NASTAR-F)

   A 2-D axisymmetric CFD analysis of the ATD TAD/Diffuser will be done using the NASTAR-F code. This analysis will verify that no flow separation is present, and also that pressure losses are minimized.

Design verification using CFD will employ the NASTAR-F code. This code will be validated by comparing its results to empirical data from two separate test cases.[1 2] In addition to demonstrating the capability of the NASTAR-F code, the validation procedure will also assess the applicability of widely used turbulence models to the TAD/Diffuser flowfield.

d. 3-D Turbulent Navier-Stokes Flow Solver (NASTAR-F)

A 3-D turbulent Navier-Stokes flow solver version of NASTAR-F will be employed to verify that secondary flows are minimized. All CFD calculations will be supplemented by full-scale flow model tests.

References:

1. Sharma, L.K. and Ostermier, B. J., "Test Report: Turnaround Duct Turbulence Test", NASA CR NAS8-40000, May 15, 1987.

2. Sandborn, V.A. and Shin, J.C., "Evaluation of Turbulent Flows in a 180 Degree Bend for Bulk Reynolds Numbers from 70,000 to 160,000", NASA CR NAS8-36354, June 1987.

Verification Complete Criteria. Verification will be considered complete when the following analyses have been completed, when it has been established that the worst operating conditions have been considered, and when the above requirements have been met.

a. Design Analysis of SSME Baseline

b. Empirical TAD/Diffuser Design Curve Analysis

c. 2-D Axisymmetric Analysis (NASTAR-F)

d. 3-D Turbulent Navier-Stokes Flow Solver (NASTAR-F)

4.1.2.12 Turbine Foreign Object Ingestion Analysis. The turbine gaspath airfoils will be designed to be resistant to Foreign Object Damage (FOD) from debris liberated upstream of the turbine interface. Analytical models of the gaspath airfoil stresses will include estimated impact stress concentrations resulting from FOD to verify capability. Fracture mechanics analysis will be utilized to predict the life of the airfoils assuming the impact damage size to be the flaw. The life calculations will include the crack growth rates in a vibratory environment and sustained load growth due to the local stress concentration and temperature environment. Verification of this life analysis will involve vibratory testing of notched airfoil specimen. Ref. paragraph 4.1.4.1.8.2, 4.1.4.2.4. The small size of the turbine airfoils in this pump make the possibility of damage even from small particles of upstream combustors a possibility. Therefore, extended periods of operation with severe damage will be unlikely. The use of borescope inspection of the first stage will be a significant factor in the reliable operation of pumps with FOD.

4.1.2.13 Static Seal and Threaded Connectors

4.1.2.13.1 Leakage Analysis. The requirement of less than 1×10^{-4} and 7×10^{-2} scc/sec helium leakage at each threaded connector or static seal, respectively, will be verified by analysis and/or testing. The design of both the static seals and the mating housing flanges duplicate the design of the current flight qualified SSME turbopump static seals and flanges except for the seal coating.

Verification Complete Criteria. Verification will be considered complete when the following analyses and test have been completed at the most severe operating conditions and the above requirements have been met:

1) Flanges/bolted joints will be stress analyzed to show that the maximum flange separation at the seal surface does not exceed TBD.

2) Bolted flange joints will be leakage tested at TBD pressure & temperature to show that helium leakage does not exceed 7×10^{-2} scc/sec.

3) Threaded connections will be leakage tested at TBD pressure & temperature to show that helium leakage does not exceed 1×10^{-4} scc/sec.

4.1.3 Performance Tests

4.1.3.1 Detail Part Level

4.1.3.1.1 Turbine Stator Flow Calibration. Flow calibration of the first and second stage stators shall be required to determine if the mechanical design of the parts provides the analytically calculated flow areas, and to determine the repeatability of the castings. Initial castings shall be flow calibrated and classes shall be estabished within ±5% of nominal. All subsequent stators will be flow calibrated as a quality assurance test.

4.1.3.2 Component Subassembly Level

4.1.3.2.1 Impeller Inlet Flowpath

4.1.3.2.1.1 Water Flow Visualization. Flow visualization and pressure measurement tests will be performed using a transparent full scale model of the pump inlet flowpath. Static tests of the inlet volute will be conducted to verify low inlet losses and minimum distortion into the impeller, followed by dynamic tests with an impeller to substantiate attainment of the suction performance objectives and to verify analytical sideload predictions. These tests will be conducted at Marshall Space Flight Center (MSFC) in the Dynamic Fluid Flow (water) Facility or an equivalent test stand.

Pump inlet flowpath tests will verify the integration of the inlet flowpath to the pump first stage impeller through definition of the loss coefficient for the inlet and verification of cavitation-free operation.

4.1.3.2.2 Damper Seal

4.1.3.2.2.1 Seal Functional Test. The damper seal demonstrator rig shall be designed to provide design verification and performance data for full-scale rough stator/smooth rotor damper seals in a cryogenic environment under actual duty cycle conditions will be utilized to demonstrate the relative damping effects of different configurations and will be used to verify rotor dynamic characteristics. Although no actual bearing springrate measurements will be taken, rotor resonance will be measured and correlated with rotor modal testing and rotor dynamics analysis to verify dynamic springrates. Leakage rates and the dampening effect on controlled instabilities will be determined to optimize the final damper seal design. Damper seal parameters planned for testing include rotor-to-stator gap, stator and/or rotor surface geometry, speed, and flows. Test data recorded will include coolant pressures and temperatures, flowrates across the damper seals, shaft deflections, vibrations, shaft speed and phase angle. These data and pre and post test inspection results will provide a basis for selecting an optimum damper seal configuration. The damper seal demonstration rig will verify damper seal coefficients and aid in the verification of rotor dynamics characteristics.

4.1.3.2.3 Lift-Off Seal

Seal evaluation tests shall be conducted in a test setup capable of simulating the turbopump operating speeds, temperatures, and fluid states.

4.1.3.2.3.1 Seal Functional Test. A test rig shall be designed for incorporation of a liftoff seal to permit functional evaluation of the seal assembly under temperature and flow conditions comparable to those on the pump. During the tests the seal shall be energized and LH2 shall be flowed through the test rig until the normal starting temperature is established. The rig design will produce liftoff of the seal as simulated pump internal pressure increases at start up. Internal instrumentation will verify the liftoff seal prestart leakage is within design criteria, that liftoff occurs within the prescribed range of pump discharge pressure, and that adequate flow is accommodated through the opened seal.

4.1.3.2.4 Turbine

4.1.3.2.4.1 Aerodynamic Test. Turbine performance shall be demonstrated in the Turbine Aero Rig Test at MSFC. Turbine rotating & static hardware provided by P&W will be tested to define turbine aerodynamic performance.

4.1.3.2.4.2 Turbine Simulator Calibration. Static turbine flow path details will be assembled in the Dynamic Fluid Flow facility at MSFC. These details will include the turbine inlet and discharge ducts, as well as a turbine simulator section to provide pressure drop and flow swirl angles reproducing conditions across the actual ATD HPFTP turbine. Flowing air through these static turbine flow path details at the same Mach number as in the subsequent hot-fire tests will calibrate the static turbine hardware prior to the Turbine Simulator Testing at P&W. The test will define the turbine simulator effective flow coefficient and swirl angle, the pressure losses of the inlet and exit ducts, and the static and fluctuating pressure environments within the fuel bowl as influenced by the turbine exit duct flow path. The data will be compared with previously obtained flow model data from full-scale water and air turbine flow path models. These tests have been coordinated with the Systems Dynamics Laboratory and appear in the SSME Dynamic Fluid Flow Air Facility Test Schedule.

4.1.3.2.4.3 Turbine Simulator Testing. Static turbine flow path details will be assembled with the P&W hot gas manifold assembly to reproduce the aerodynamic environment in the SSME-HGM. This testing will verify the static pressure gradient across the turbine axis, the system pressure loss from the turbine exit to the main injector assembly entrance, and the circumferential pressure gradient, and verify that no fluctuating pressures are produced by separated and vortex flow regions.

4.1.3.2.5 Turbine Exit Gas Path

4.1.3.2.5.1 Water Flow Visualization. Flow visualization and pressure measurement tests will be performed using a transparent full scale model of the turbine turnaround duct/hot gas manifold. These tests will be conducted at Marshall Space Flight Center (MSFC) in the Dynamic Fluid Flow (water) Facility or an equivalent test stand. Turbine turnaround duct/hot gas manifold tests will define the flow distribution and pressure patterns. Flowpath total pressure loss and static pressure recovery will also be verified.

4.1.3.2.5.2 Air Flow Characterization. Flow pressure measurement tests will be performed using a full-scale model of the turbine turnaround duct/hot gas manifold. These tests will be conducted at Marshall Space Flight Center(MSFC) in the Dynamic Fluid Flow (air) Facility or an equivalent test stand. These tests will provide more accurate verification of specific flow characteristics obtained in the water flow tests.

4.1.3.3 Component Level. The component tests shall be performed with the turbopump assembly mounted in a test adapter and installed on test facility E-8. The pump shall be supplied with liquid hydrogen from a pressurized supply tank. The turbine power shall be supplied by the facility preburner and chamber assembly which is mounted in the correct attitude (engine condition). Turbine discharge flow is collected and ducted to a discharge port by the facility hot gas manifold., This system shall be capable of operating the high pressure fuel turbopump to 109% + 2 σ (tolerance adders) of rated engine conditions. The system provides a simulation of engine flowpath geometries and conditions at the turbine inlet and discharge and pump inlet and discharge.

4.1.3.3.1 Test Conditions. Testing of the HPFTP shall be performed using liquid hydrogen as the test fluid. Fully instrumented development turbopumps will be used to confirm design conditions by measuring flowpath pressures, both hardware and flowpath temperatures, and rotor travel/position.

4.1.3.3.2 Turbopump Assembly Test. The turbopump test setups shall be operated on E-8 test facility 1) to provide a functional evaluation of the pump, turbine, rotor support, and rotor thrust control systems, and 2) to verify multiple mission capability of the turbopumps by running "SSME thermal-cycle-life equivalent" start and shutdown transients. During E-8 level testing, component performance maps (pump efficiency vs. flow, turbine efficiency vs. velocity ratio, flow parameters, etc) will be generated. This empirical information will be fed back into the DTM to develop engine transfer functions for use in determining control stability margins. The turbopumps will be characterized into computer code and installed into the ICD versions of the ATD Power Balance Model (ATD-PBM) and the ATD Digital Transient Model (ATD-DTM). These models will be used to evaluate the following parameters as they interface with the remainder of the SSME, as specified by the ICD.

Parameter	Requirement Source
a. Pump head rise	ATD-PBM
b. Pump efficiency	ATD-PBM
c. Control stability margin	ATD-DTM
d. Start capability	ATD-DTM
e. Shutdown capability	ATD-DTM
f. Transient response	ATD-DTM
g. Engine transfer function	ATD-DTM
h. Turbine performance (Efficiency and flow parameters)	ATD-PBM
i. Rotor power requirements	ATD-PBM
j. Turbine coolant effectiveness	ATD-PBM, turbine coolant flow and thermal models
k. Turbopump vibration	TBD g's maximum
l. External leakage	TBD scc/sec helium total
m. Bearing operating temp	TBD °R (maximum)
n. Liftoff seal leakage	300 scim (maximum)
o. Breakaway torque	TBD in lb
p. Insulation effectiveness	TBD

4.1.3.3.3 Pump Evaluation

4.1.3.3.3.1 Hydrodynamics Test. The following parameters shall be demonstrated on the engine cycle point requirements.

Parameter

a. Efficiency
b. Pressure Rise
c. Delivered flow
d. Suction specific speed

4.1.3.3.3.2 Stability Test. Pump stability will be maintained during all performance testing to verify that operation over the engine operating range is stable.

4.1.3.3.3.3 NPSP Determination. Performance testing will be conducted to verify that at the minimum engine cycle NPSP requirements, the pump operation is stable with less than 3% head rise fall-off over the engine operating range.

4.1.3.3.3.4 Off Design Tests. Off design tests will be conducted to map the pump hydraulic margins and to determine thrust balance and other internal flow system dynamics.

4.1.3.3.4 Bearing Evaluation

4.1.3.3.4.1 Bearing Temperature Test. The bearing outer race temperatures shall be monitored on component tests and shall not exceed the following maximum values:

a. Pump bearing: TBD °R
b. Turbine bearing: TBD °R

Bearing coolant inlet and exit temperature and pressures will also be measured.

4.1.3.3.5 Turbine Evaluation

4.1.3.3.5.1 Turbine Coolant System Evaluation. The performance of the turbine coolant system shall be evaluated to determine the adequacy of the system to maintain the required temperature environment to the turbine disks, turbine stationary support structure, and rear housing. The system shall be acceptable if the following coolant states (pressure and temperature) and measurable metal temperatures meet performance requirements:

a. Turbine coolant flow rate

b. Turbine coolant inlet temperature and pressure

c. Turbine blade attachment coolant mix temperature and pressure

d. Disk front face and back face coolant temperature and pressure

e. Stationary structure coolant temperature and pressure

f. Stationary support metal temperature

4.1.3.3.6 Chilldown and Prelaunch Service Free Demonstration Test. Demonstrate that the ICD head/flow conditions for propellant delivery during prechill will satisfactorily condition turbomachinery within the sixty (60) minute chilldown period. The turbopump shall be instrumented internally at critical locations to verify results. Demonstrate that the turbopump will function at any time within 24 hours under propellant loaded conditions without ground servicing.

4.1.3.3.7 Thrust Balance Capacity and Stability. Testing shall be conducted to determine thrust balance capability and stability, including assessment of sensitivity to clearances and other unit-to-unit variables. Based on performance evaluation, proximity probe data, thrust balance cavity pressure measurements, and visual inspection of the impeller, dynamic seal surface and bearing, the thrust balance capacity and stability will be verified.

4.1.3.4 Engine Level. Engine system testing of the high pressure fuel turbopump shall provide the final functional verification of the performance parameters. Engine testing shall provide input to the turbopump data bank to demonstrate that the performance characteristics are compatible with the engine cycle and the performance variation meets the engine performance and life criteria as specified in the CEI Specification.

4.1.3.4.1 Turbopump Assembly. The high pressure fuel turbopump shall be subjected to a calibration that covers the FPL, RPL, and MPL conditions:

This test series shall be repeated four times on each of two sets of hardware. Data points within the test series may be combined so that the total number of tests is TBD.

4.1.3.4.2 Turbopump Assembly Acceptance Test. The turbopump test shall be operated at the NASA engine test facility to demonstrate the engine-component compatibility. The turbopump assembly shall be accepted if the following engine Power Balance Model (ATD-PBM) and Digital Transient Model (ATD-DTM) conditions and turbopump health parameters are met during engine test.

a.	Pump head rise	ATD-PBM
b.	Pump efficiency	ATD-PBM
c.	Control stability margin	ATD-DTM
d.	Start compatibility	ATD-DTM
e.	Shutdown Compatibility	ADT-DTM
f.	Transient response	ATD-DTM
g.	Engine transfer function	ATD-DTM
h.	Turbine performance	ATD-PBM
i.	Rotor power requirements	ATD-PBM
j.	Turbine coolant effectiveness	ATD-PBM
k.	Turbopump vibration	TBD g's maximum
l.	External leakage	TBD scc/sec
m.	Bearing operating temperature	TBD °R (maximum) turbine roller bearing TBD°R (maximum) pump ball bearing
n.	Liftoff seal leakage	300 scim (maximum)
o.	Breakaway torque	TBD in-lb
p.	Insulation effectiveness	TBD

Verification Complete Criteria. Verification will be considered complete when turbopump has been subjected to tests and successfully met the following requirements:

1. Operation demonstrated for the entire operating range from MPL to FPL.
2. Performance compatible with the engine ATD-PBM requirements at each power level.
3. Disassembly inspection of the turbopump reveals no damage.
4. Performance within specification while being influenced by the conditions at the functional interfaces.

5. Power rate changes meet ICD 11372 requirements.
6. Performance meets acceptance test criteria after accelerated endurance testing over an equivalent overhaul period.

4.1.4 Design Structural Tests. Preliminary tests planned are presented in Table IV-2. Detail description of each test at the four DVS test levels is given below.

Table IV-2. *Design Structural Tests*

Detail Part	Pressure	LCF Life	EDM Sample	Spin	Spin Burst	Vibration	Flow	Rig	Cycle	Other
Housings	X		X			X				
Bearings								X	X	Hardness
Impellers			X	X	X	X		X		Wear, Photoelastic
Lift-Off Seal						X	X	X	X	
Turb. Inlet Duct	X					X				
Turnaround and Exit Ducts	X					X				
Turbine Disk/ Shaft				X	X	X		X		
Turbine Blades		X				X				Photoelastic (stage 2)
Turbine Stator Vanes		X				X				
Bellows	X					X				

Subassembly	Impedance	Spring Rate	Insulation	Vibration
Pump Brg. Support		X		
Turbine Brg. Support		X		
Rotor Assembly	X			
Turbine Bladed Rotor				X
Turbine Ducts and Stators				X
Housing Insulation			X	

Component	LCF Life	Critical Speed	Condition Monitor	Wear	Vibration	Leakage	Insulation	Over Speed	Water Damage
Turbopump Assy.	X	X			X	X	X	X	X
Housing Assy.			X		X	X	X		
Bearing			X						
Thrust Balance				X					

Engine	LCF Life	Fluid Dynamics	Blade Creep	Vibration	Water Damage
Turbopump Assy.	X	X	X	X	X

4.1.4.1 Detail Parts

4.1.4.1.1 Housings

4.1.4.1.1.1 Pressure Test. All housings shall be assembled in tool fixtures or mating parts to provide interface restraints, load paths, etc. Strain gage instrumentation will be attached at locations of predicted high stress, or at locations of stress concentrations defined by brittle lacquer coating analysis. Direct deflection measurements may also be recorded. Each vessel will be pressurized using water or hydraulic oil in a room temperature environment. The housings are acceptable if the deflections are within acceptable limits and the stresses and strains are found to meet the requirements set forth in MSFC-STD-505A, including burst pressure test of 1.5 x design limit pressure. Acceptable deflection limits will be defined as stress analysis matures.

Table IV-3. *VIBRATION TESTS*

COMPONENT Reference Paragraph	MODAL	HOLO-GRAPHY	STRESS COAT	SHAKER TABLE	HCF	SPIN PIT
HOUSINGS 4.1.4.1.1.2 4.1.4.2.6.3	X	X	+	+		
IMPELLER 4.1.4.1.3.3	X	X	+	+		
LIFT-OFF SEAL 4.1.4.1.4.2	X	X	+	+		
TURBINE INLET DUCT 4.1.4.1.5.2	X	X	+	+		
TURNAROUND DUCT 4.1.4.1.6.2	X	X				
TURBINE DISK 4.1.4.1.7.4	X	X	+	+		
TURBINE BLADES 4.1.4.1.8.2 4.1.4.2.4.1	X	X	X	X	X	X
TURBINE VANES 4.1.4.1.9.1	X	X	+	+		
TURBINE INLET BELLOWS 4.1.4.1.10	X	X	+	+		
TURBINE STRUCTURAL ASSEMBLY 4.1.4.2.5.1	X	X	+	+		

+ Optional Testing

4.1.4.1.1.2 Vibration Test. Vibratory force transducers will be used at room temperature to excite the housings over a range of frequencies covering all possible turbopump excitation. Laser holograms and/or model impact will be used to define resonant mode shapes and frequencies. This data will be compared with finite element analysis to verify that the housings have $\geq$ 10% frequency margin at turbopump steady state conditions.

For housings that have resonant responses, brittle lacquer, non-contacting infrared, or strain gage vibratory testing will be used to verify that the dynamic stress associated with the resonant conditions is not excessive over the turbopump operating range of 65% RPL to 109% RPL.

4.1.4.1.1.3 Elox Sample Test. Microstructure specimens and laboratory test bars shall be required to certify the electrical discharge machining technique. The process shall be acceptable if the depth of the recast layer is small enough to assure removal in the final machining and polishing operation.

4.1.4.1.2 Bearing

4.1.4.1.2.1 Roller Bearing Outer Race Hardness Test. The first outer race shall be sectioned to evaluate the case and core hardness values and to evaluate the depth of the hardened case. The part shall be acceptable if the following values are attained:

a. Core hardness: 40 Rc maximum
b. Case hardness: 58-62 Rc
c. Depth of Case: 0.037 - 0.053 inch

This check shall be conducted on a representative sample from each subsequent carburizing and heat treatment lot.

4.1.4.1.2.2 Bearing Environmental Test Rigs. Bearing evaluation tests shall be conducted in test rigs capable of testing two pump end bearings or two turbine end bearings simultaneously. The bearings shall be loaded to simulate the maximum steady and transient bearing loads at speeds up to 38,000 rpm. Speed, load and coolant flow will be varied parametrically to determine bearing load capability. Loads shall be provided to simulate or exceed turbopump operating conditions up to 109% RPL, as defined in the following table. Cooling flows will be run at conservative levels to demonstrate adequate margin for the turbopump.

a. Coolant Flow Rate Per Bearing:

(1)	Pump Bearing:	0.3* pound/second
(2)	Turbine Bearing:	TBD pound/second

b. Pump Ball Bearing Loads:

(1)	Radial loads:	475* pounds
(2)	Axial loads:	800* pounds (steady) 15,000* pounds(transient)

c. Turbine Roller Bearing Loads:

(1)	Radial loads:	3350
(2)	Axial Displacement:	± .015 inches

*Based on current analyses

4.1.4.1.2.3 Service Life Test-Roller Bearing. To demonstrate twice the operational life of the roller bearing design, four (4) bearings shall be operated at the above calculated operating condition for 15 hours of simulated mission endurance cycles at the above stated coolant flow rate. A minimum of 120 acceleration and deceleration cycles shall be demonstrated. The bearing configuration shall be acceptable if all bearings successfully complete the above test program and, on disassembly, inspection shows no structural defect and roller end wear is less than a total of 0.010 inch.

4.1.4.1.2.4 Serivce Life Test - Ball Bearing. To demonstrate twice the operational life of the ball bearing design, four (4) bearings shall be operated at the above calculated operating conditions, respectively, for 15 hours of simulated mission endurance cycles. A minimum of 120 rapid acceleration and deceleration cycles shall be demonstrated. The bearing configuration shall be acceptable if all bearings successfully complete the above test program and, on disassembly, inspection shows no structural defect and ball bearing wear is less than a TBD amount (in.).

4.1.4.1.2.4.1 Pump ball bearing axial load-deflection will be determined over the operational speed range. Radial load-deflection and damping will be determined at critical speed conditions with a damper seal rig.

4.1.4.1.3 Impellers

4.1.4.1.3.1 Spin Test Evaluation. The first, second and third stage impellers shall be individually subjected to spin tests to verify analytical predictions of local maximum strain. These stress evaluations consist of static strain-gage surveys at speeds ranging from zero to the maximum operating speed as corrected for material property differences at room temperature.

4.1.4.1.3.2 Spin Burst Test. An impeller from each stage shall be subjected to a limit load spin test upon completion of the above spin test. The impeller shall demonstrate its mechanical integrity to 122% design limit load speed at room temperature after which the impeller will be dimensionally inspected for plastic deformation. Verification of spin burst margin and calculation of ultimate burst conditions will be based on analysis of these speed and plastic growth data.

4.1.4.1.3.3 Vibration Test. Vibration tests shall be performed on the impellers to determine the resonant frequency of the hub and shroud. The impeller shall be acceptable if the demonstrated frequencies are within the requirements specified in P&W Structural Design Criteria, and there are no diametrals in the operating range thru at least 12E.

Critical excitations are:

1. Rotor orders: 1E, 2E, 3E and 4E
2. Volute collector passing at primary and second order
3. Upstream (inlet) struts passing at primary and second order
4. Difference between upstream and downstream passing characteristics at primary order.

4.1.4.1.3.4 Wear Tests. Representative impeller and housing wear pad materials will be used in tests to characterize the wear rate from surface to surface contact of the thrust balance system during pump start and shutdown conditions.

4.1.4.1.3.5 EDM Sample Test. Microstructure specimens and laboratory test bars shall be required to certify the electrical discharge machining technique. The process shall be acceptable if the depth of the recast layer is thin enough to assure removal in the final machining and polishing operation.

4.1.4.1.3.6 Photoelastic test. Photoelastic stress analysis tests using three-dimensional structural models of the first stage impeller will be conducted at P&W to verify the results of the finite-element stress analyses. The structural models will be environmentally loaded, including spin loads, heated to the material transition temperature, held at load, and then cooled under load to freeze the maximum load stresses in the model. Polariscope analysis of induced stresses in model sections at critical locations will verify finite element analysis predictions and define locations of concentrated stress.

4.1.4.1.4 Lift-off Seal

4.1.4.1.4.1 Cyclic/Wear Test. The liftoff seal shall be installed in test rigs that simulate the pump seal area configuration and the turbopump operating speeds, temperatures, and fluid states. A pretest functional check will assure the design criteria for closed position leakage, opening pressure, and open flowrate meet requirements. A cyclic test of the liftoff seal, alternately cycling between the seal maximum open differential pressure and the closed differential pressure, will verify the 240 cycle life requirement. The post test closed position leakage, opening pressure, and open flowrate shall be within TBD% of the pretest measurement.

4.1.4.1.4.2 Vibration Test. Vibration tests shall be conducted on the liftoff seal assembly with the bellows in the extended (open) position to determine its resonant frequency. These data shall be used to evaluate the design when the dynamic vibration characteristics of the turbopump test setup, powerhead test setup, and the engine system have been ascertained on the initial operational tests. The seal shall be acceptable if the resonant frequencies identified meet or exceed the ten (10) percent margin from defined critical excitations.

4.1.4.1.4.3 Bond Sample Test. Samples of the seal convolution and bonded joints shall be submitted for evaluation of the microstructure and mechanical properties. The bonded joint quality shall comply with the pre-established quality requirements specified.

4.1.4.1.5 Turbine Inlet Duct

4.1.4.1.5.1 Proof Pressure Test. The turbine inlet duct assembly shall be assembled to the appropriate test fixture which permits pressurization of the structure at room temperature to simulate an equivalent of 1.2 times the maximum operating pressures.

The turbine inlet duct assembly will be proof tested with strain gages strategically located at critical areas predicted by NASTRAN analysis. The duct assembly shall be acceptable if the maximum values of the plastic strain do not exceed 0.2%.

4.1.4.1.5.2 Vibration Test. Vibration testing shall be conducted on the turbine inlet duct to determine its resonant frequency. These data shall be used to evaluate the design when the dynamic vibration characteristics of the turbopump test setup, powerhead test setup, and the engine system have been ascertained on the initial operational tests. The duct shall be acceptable if the resonant frequencies identified meet or exceed the ten (10) percent margin from defined critical excitations.

Critical exitations are:

1. Rotor orders: 1E, 2E, 3E and 4E
2. Downstream blade passing (1st stage only)
3. Primary preburner instabilities

4.1.4.1.6 Turnaround and Exit Ducts

4.1.4.1.6.1 Proof Pressure Test. The turnaround and exit duct assembly shall be assembled to the appropriate test fixture which permits pressurization of the structure to simulate an equivalent of 1.2 times the maximum operating pressures.

The turnaround and exit duct assembly will be proof tested with strain gages strategically located at critical areas predicted by NASTRAN analysis. The duct assembly shall be acceptable if the maximum values of the plastic strain do not exceed 0.2%.

4.1.4.1.6.2 Vibration Test. Vibration testing shall be conducted on the turbine exit turnaround duct to determine its resonant frequency. These data shall be used to evaluate the design when the dynamic vibration characteristics of the turbopump test setup, powerhead test setup, and the engine system have been ascertained on the initial operational tests. The duct shall be acceptable if the resonant frequencies identified meet or exceed the ten (10) percent margin from defined critical excitations.

4.1.4.1.7 Turbine Disk/Shaft

4.1.4.1.7.1 Rig Load Test. A strain gage load test of the tie bolt shall be performed to verify the accuracy of the tiebolt stretch prediction.

4.1.4.1.7.2 Spin Test Evaluation. The turbine disk, with a set of turbine blades shall be assembled on a spin arbor. The disk/arbor shall be dynamically balanced, and subjected to spin tests to verify analytical predictions of local maximum strain range. These stress evaluations consist of static and vibratory strain-gage surveys of components being spun in a spin pit rig at speeds ranging from zero to the maximum operating speed as corrected for material property differences at room temperature.

4.1.4.1.7.3 Spin Burst Test. One disk shall be subject to a limit load spin test upon completion of the above spin test. The disk shall demonstrate its mechanical integrity to 122% design limit load, after which the disk will be dimensionally inspected for plastic deformation. Verification of spin burst margin and calculation of ultimate burst conditions will be based on analysis of these speed and plastic growth data.

4.1.4.1.7.4 Vibration Test. The turbine disk shall be excited to determine vibratory resonant modes and frequencies. The disk shall be acceptable if a margin of more than ten (10) percent exists between any resonant mode and the rotor orders 1E, 2E, 3E, and 4E at conditions of sustained operation, and there are no diametrals in the operating range thru at least 12E.

4.1.4.1.8 Turbine Blades

4.1.4.1.8.1 Photoelastic Test. Photoelastic stress analysis tests using three-dimensional structural models of the blades from the second stage turbine will be conducted at P&W to verify the results of the finite-element stress analyses. The structural models will be environmentally loaded, including spin loads, heated to the material transition temperature, held at load, and then cooled under load to freeze the maximum loadstresses in the model. Polariscope analysis of induced stresses in model sections at critical locations will verify finite element analysis predictions.

4.1.4.1.8.2 Vibration Test. Representative samples of both first and second stage turbine blades shall be subjected to vibration testing to determine their fundamental vibratory mode resonant frequencies. The blades shall be mode-shape signatured using holographic techniques in order to accurately describe the blade mode shapes at these resonant frequencies. In addition, HCF and turbine spin rig testing will be conducted per Table IV-3.

Critical excitations are:

1. Rotor orders: 1E, 2E, 3E, and 4E
2. Upstream (inlet) struts passing at primary and second order
3. Difference between upstream and downstream passing characteristics at primary order.
4. Number of immediate upstream or downstream struts at primary order and twice primary order
5. Number of upstream struts on stage removed at primary order
6. Instrumentation probe orders determined by Fourier Analysis
7. Number of blade outer gas seal segments/slots

4.1.4.1.8.3 Low Cycle Fatigue Test. Test specimens with geometries similar to the turbine blade airfoils shall be tested in the MSFC thermal cycle test facility. The rig burns hydrogen and oxygen and cycles between 160°R and 2160°R. Maximum pressure level is 2500 psia. The rapid start and shutdown rates of approximately 7000°R/sec cause a thermal shock on the specimens similar to that experienced in the SSME turbines hot gas streams. The rig provides for comparative evaluation of LCF capabilities of various geometries and materials in a realistic thermal shock environment. This rig does not simulate centrifugal loading since the airfoils are stationary.

Actual blades with representative surface finishes will also be tested using pyrometer instrumentation being developed for TTB.

4.1.4.1.9 Turbine Vanes

4.1.4.1.9.1 Vibration Test. Vibration testing shall be conducted on the turbine vanes to determine their resonant frequencies. The turbine stators shall be acceptable if the resonant frequency provides at least a ten (10) percent margin on all identified critical excitations.

Critical excitations are:

1. Rotor orders: 1E, 2E, 3E, and 4E
2. Volute collector passing at primary and second order
3. Upstream (inlet) struts passing at primary and second order
4. Difference between upstream and downstream passing characteristics at primary order.

4.1.4.1.9.2 Low Cycle Fatigue Test. Test specimens with geometries similar to the turbine vane airfoils shall be tested in the MSFC thermal cycle test facility. The rig burns hydrogen and oxygen and cycles between 160°R and 2160°R. Maximum pressure level is 2500 psia. The rapid start and shutdown rates of approximately 7000°R/sec cause a thermal shock on the specimens similar to that experienced in the SSME turbines hot gas streams. The rig provides for comparative evaluation of LCF capabilities of various geometries and materials in a realistic thermal shock environment. Vane specimens representing as-cast and finished surfaces will also be tested using available instrumentation (pyrometer, strain gage, etc.) being developed for TTB.

4.1.4.1.10 Turbine Inlet Bellows and Shield

4.1.4.1.10.1 Proof Pressure Test. The turbine inlet bellows and shield assembly shall be assembled to the appropriate test fixture which permits pressurization of the structure at room temperature to simulate an equivalent of 1.2 times the maximum operating pressures.

The turbine inlet bellows and shield assembly will be proof tested with strain gages strategically located at critical areas predicted by NASTRAN analysis. The bellows and shield assembly shall be acceptable if the maximum values of the plastic strain do not exceed 0.2%.

4.1.4.1.10.2 Vibration Test. Vibration testing shall be conducted on the turbine inlet bellows and shield to determine its resonant frequency. These data shall be used to evaluate the design when the dynamic vibration characteristics of the turbopump test setup, powerhead test setup, and the engine system have been ascertained on the initial operational tests. The bellows and shield assembly shall be acceptable if the resonant frequencies identified meet or exceed the ten (10) percent margin from defined critical excitations.

Critical excitations are:

1. Rotor orders: 1E, 2E, 3E and 4E
2. Primary preburner instabilities
3. Downstream blade passing (first stage only).

4.1.4.2 Component Subassemblies

4.1.4.2.1 Pump Bearing Support System

4.1.4.2.1.1 Spring Rate Test. The static (radial) stiffness (springrate) of the pump end inlet housing and respective bearing support assembly (including the turbopump housings) will be determined by loading each bearing support bore in a radial direction and measuring the deflection. These radial deflections will be correlated to input load to verify that the bearing loadpath exhibits the minimum spring rate calculated to meet rotor critical speed criteria.

4.1.4.2.2 Turbine Bearing Support System

4.1.4.2.2.1- Spring Rate Test. The static (radial) stiffness (springrate) of the turbine end rear housing and respective bearing support assembly (including the turbopump housings) will be determined by loading each bearing support bore in a radial direction and measuring the deflection. These radial deflections will be correlated to input load to verify that the bearing loadpath exhibits the minimum spring rate calculated to meet rotor critical speed criteria.

4.1.4.2.3 Rotor Assembly

4.1.4.2.3.1 Modal Test. The predicted fuel pump assembly critical speeds shall be checked by conducting modal impact vibration tests on the rotor assembly alone, in a nonrotating free-free state, without turbine blades. The rotor shall be supported from a beam with elastic cords of known spring rate at both bearing locations. Accelerometers, attached to the rotor at eight axial locations, shall record the induced vibrations during the vibration test with a frequency sweep of from 200 to 2,000 Hertz. The rotor assembly shall be acceptable if the natural bending frequencies are within +20/-0 percent of the predicted values. The measured frequencies and mode shapes will be used to revise the rotor assembly analysis as required.

4.1.4.2.4 Turbine Bladed Rotor

4.1.4.2.4.1 Vibration Test. A dynamic evaluation of turbine blade vibratory response shall be conducted on a fully-bladed turbine rotor. This rotor shall have dynamic strain gages installed on representative blades in all stages at locations of maximum strain defined by analytical predictions and individual holographic tests and blade stress coat per Table IV-3 results. This instrumented rotor shall be rotated to design speed in a P&W spin pit facility, with blade vibratory excitation provided by air jets or piezioelectric crystals. Blade vibratory responses over a range of excitations shall be recorded and analyzed to demonstrate no blade resonance at conditions of continuous operation in the turbopump speed range corresponding to 65% RPL to 109% RPL.

4.1.4.2.5 Turbine Ducts and Vanes

4.1.4.2.5.1 Turbine Structural Resonance Test. Vibration testing of the assembly of the turbine inlet duct, the turnaround and exit ducts, the turbine inlet bellows assembly and the turbine vanes shall be conducted to determine the resonant frequency of the assembly. These data shall be used to evaluate the design when the dynamic vibration characteristics of the turbopump test setup, powerhead test setup, and the engine system have been ascertained on the initial operational tests. The duct shall be acceptable if the resonant frequencies identified meet or exceed the ten (10) percent margin from defined critical excitations. If resonances occur within the defined margins, impedance testing shall be conducted to determine that stress levels experienced during operation conditions do not approach critical levels.

4.1.4.2.6 Housings and Externals.

4.1.4.2.6.1 Housing Insulation Test. An insulation durability test will be performed on a turbopump housing assembly complete with insulation to assure that housing insulation remains intact when subjected to the following conditions:

a. Cool to cryogenic temperature (simulated prestart conditioning)
b. Ambient temperature vibration test (simulated launch)
c. Ambient temperature vacuum environmental test (simulated orbital)

4.1.4.2.6.2 Static Seal and Threaded Connectors Leakage Test. A leakage test of the turbopump external housings with all threaded connectors and static seals will be performed at TBD leak check pressure to verify a total leakage of less than 1×10^{-4} scc/sec helium at each connector and less than 7×10^{-2} scc/sec helium at each separable joint.

4.1.4.2.6.3 Vibration Test. A modal test of the housing assembly without plumbing and a vibration test of the turbopump housing assembly with P&W unique external plumbing and instrumentation will be performed to assure parts do not resonate within the turbopump interface vibration shock, and acoustic load requirements specified in the CEI specification.

4.1.4.3 Component

4.1.4.3.1 Turbopump Assembly

4.1.4.3.1.1 Rotor Dynamics and Vibration Test. The turbopump will be instrumented with accelerometers and proximity probes to measure housing and rotor vibration levels and characteristics. Proximity probes will measure radial shaft deflections for correlation with accelerometer vibration measurements of housing locations. Data will then be used in conjunction with analytical predictions to verify and insure acceptable vibration levels as established by rotordynamic criteria.

4.1.4.3.1.2 LCF Life Testing. The turbopump duty cycle low cycle fatigue (LCF) life of 60 missions, will be demonstrated in accelerated mission testing on the P&W E8 test facility. The transient characteristics of the tests, including starts, power ramps and shutdowns will be controlled to provide an SSME thermal strain cycle life equivalency.

An optical pyrometer will be utilized to measure turbine airfoil thermal response during the LCF testing.

4.1.4.3.1.3 Impeller and Thrust Bearing Flow Erosion Evaluation Test. The flow erosion resistance of the third impeller thrust balance faces, rub faces on the associated housing, and the thrust face on the pump end of the shaft shall be evaluated to determine the rate of erosion and thrust balance performance deterioration. The thrust balance pressures on the impeller shall be monitored along with the axial position of the rotor during all testing as described in Paragraph 4.1.3.4.1. Pre and post test measurements will be correlated with the measured data to determine the extent of erosion on thrust balance capability and its effects on stability. The operating system impeller, and rub faces shall be acceptable if the rate of erosion does not decrease the thrust balance capability margin in excess of TBD percent, does not change the stability of the thrust balance system, and does not affect the rotor vibrations in excess of the total vibration limits of TBD G's.

4.1.4.3.1.4 Bearing Evaluation. The bearing outer race temperatures shall be monitored on component tests and shall not exceed the following maximum values;

a.	Pump ball bearing	TBD	°R
b.	Turbine roller bearing	TBD	°R

4.1.4.3.1.5 Lift-Off Seal Test. During turbopump operation in the P&W E-8 test facility, cooling passage pressures will be compared with rig flows/differential pressures to assure that the liftoff seal flow is not altered by rotor dynamics, structural resonance, or flow instability.

4.1.4.3.1.6 Drying Purge. Propellant combustion products (water) will be removed by a drying nitrogen purge.

4.1.4.3.2 Housings and Externals

4.1.4.3.2.1 Static Seal and Threaded Connectors Leakage Test. A leakage test of the turbopump external housings with all threaded connectors and static seals will be performed at TBD leak check pressure to verify a total leakage of less than 1×10^{-4} scc/sec helium per connector and less than 7×10^{-2} scc/sec helium per separable joint.

4.1.4.3.2.2 Insulation Durability Test. Turbopump component testing on the E-8 facility will verify that the insulation will remain intact through 60 thermal cycles to cryogenic conditions.

4.1.4.4 Engine

4.1.4.4.1 Turbopump Assembly

4.1.4.4.1.1 Vibration Test. Response of the critical turbopump parts to excitation by the total engine system will be determined by monitoring the turbopump vibrations with accelerometers attached to the external flanges and housings and by monitoring rotor axial movements with internal proximity probes.

4.1.4.4.1.2 Fluid Dynamics Test. High frequency pressure transducers in the turbopump shall be monitored during engine testing throughout the entire range of operations, including FPL to determine the flow dynamics of the pump and turbine systems. The fluid operating frequencies established by the combined engine system shall be compared to the detail resonant frequencies to ascertain that no detail parts are excited by the engine.

4.1.4.4.1.3 Creep Test. Dimensionally precalibrated turbine blades shall be incorporated in the turbine of the first turbopump test setup. A creep notch shall be machined in the leading or trailing edge tip of each blade. The turbine shall be operated at TBD rpm and TBD °R for TBD hours. The test setup shall be disassembled and the retest calibration measurements shall be compared to the post-test dimensions. The blades shall be accepted if the TBD hour, 1% creep allowance is not exceeded on any part. The post-test blade microstructure shall be evaluated by nondestructive testing and microstructure examination and compared with the as-received inspection reports.

4.1.4.4.1.4 RPL/MPL and FPL Duration. Continuous turbopump operation at engine power level between MPL and RPL for 823 seconds, and continuous operation at FPL power level for 754 seconds will be demonstrated separately at NSTL.

4.1.4.4.1.5 Duty Cycle / LCF Life. Design turbopump operation time capability of 7.5 hours including 60 starts and associated mission power level profiles to any power level up to 109% will be demonstrated at NSTL. Analysis of component testing in the E-8 Facility and engine testing will verify this capability prior to delivery of a turbopump to NSTL.

An optical pyrometer will be utilized to measure turbine airfoil thermal response during engine level testing at NSTL based upon E-8 experience. The turbine inlet gas temperature profile will also be recorded by high density thermocouples in an ARTS (Automated Recording Temperature Survey) package during NSTL testing.

4.1.5 Maintainability, Reliability, Safety and Quality

4.1.5.1 Interchangeability/Replaceability. Requirement - To verify the design requirements for Interchangeability/Replaceability.

Analysis. The specified turbopump requirements will be verified by reviewing and correlating the engineering drawings and specifications with all applicable documents of Section 2. It will be assured that the requirements have been followed and are properly documented and implemented. Dimensional stack-ups will also be accomplished, where applicable, to assure that the requirements have been met at the drawing tolerance extremes. Turbopump performance will be compiled from all engine system tests during design verification. Statistical evaluation of these results will be used for verification of functional interchangeability.

Replaceability-Demonstration. A demonstration shall be performed to verify the ability to successfully remove and replace the ATD turbopump as an LRU (Line Replaceable Unit). The demonstration will be performed in an environment which closely simulates the actual conditons in which the ATD turbopump would normally be replaced.

4.1.5.2 Manufacturing Processes

Requirement. To verify that turbopump assembly and components used for development purposes, including verification testing, are manufactured using procedures, controls, and facilities identical to those employed for deliverable turbopumps.

Analysis. All turbopump hardware fabrication and assembly procedures shall be formulated prior to initiating turbopump fabrication. Adherence to these procedures or modifications thereof, for all hardware fabricated during the verification period shall be verified by contractor Quality Assurance. Certification that all phases of fabrication and assembly were accomplished in predesignated areas of the contractor and/or vendor facilities shall be part of this verification.

4.1.5.3 Identification and Marking. Requirement - To verify the design requirements for Identification and Marking.

Analysis. The specified turbopump requirements will be verified by reviewing and correlating the engineering drawings and specifications with all applicable documents of Section 2. It will be assured that the requirements have been followed and are properly documented and implemented.

4.1.5.4 Reliability

Requirement. To verify the design has eliminated or minimized failure modes which can adversely affect crew, vehicle or mission.

Analysis. The design will be verified by Design Review and preparation of a Failure Mode Effect and Criticality Analysis. Test results will be assessed, malfunction reports will be assigned for failure analysis, and corrective action evaluated.

Verification Complete Criteria. Verification is by Reliability Data Requirements.

4.1.5.5 Safety

Requirement. To verify that the turbopump design features have been selected in such a manner to ensure maximum personnel safety and minimize the potential for equipment and property damage.

Analysis. A hazard analysis using the applicable P&W techniques and based on descriptions of the hardware design, objectives, and activities will be prepared to define and categorize the hazard levels and develop the required corrective action to reduce "catastrophic" or "critical" hazards for which safety or warning devices and special procedures cannot be developed or provided to effectively counteract the hazard shall be specifically reported to System Safety and Program Management. This report shall describe the hazardous conditions, the hazard classification, indicate its effect, define the cause, and develop the rationale for accepting the resulting risk.

Verification Complete Criteria. Verification is by Safety Data Requirements.

4.1.5.6 Quality Assurance

Requirement. To verify that the design provides appropriate controls of material, fabrication, cleaning, and tests to demonstrate conformance to applicable design criteria for the turbopump assembly.

Analysis. Analysis of the turbopump assembly hardware fabrication, assembly, and test quality requirements and preparation of quality planning shall be formulated prior to the operation being performed. Adherence to these procedures will be by inspection verification.

Verification Complete Criteria. Verification is by Quality Data Requirements.

4.1.5.7 Maintainability

4.1.5.7.1 Inspectibility. Visual inspectibility of the turbopump will be demonstrated for external damage and leakage and for internal borescoping of turbine, pump section and bearings condition.

4.1.5.7.2 Monitoring. Automatic turbopump monitoring and checkout provisions will be demonstrated to be unnecessary. However a turbine optical pyrometer and bearing health monitor will be developed as optional ground test diagnostic tools.

4.1.5.7.3 Special Servicing. Special servicing will be demonstrated to be unnecessary for the turbopump.

4.1.5.7.4 Access. Access will be demonstrated to be nonrestrictive to interface hardware attachment points, separable joints, manual rotor rotation, and internal borescope inspection.

4.1.5.7.5 Handling. Suitable attachment points will be provided for handling the turbopump during handling and replacement on the engine.

4.1.5.7.6 Repair. A sixty (60) start capability will be demonstrated on the turbopump without any repair actions.

4.1.5.8 Failure Mode Effect and Criticality Analysis

Requirement. To verify that all failure modes of the pump components are identified and their effect on engine and vehicle operation is determined.

Analysis. A Failure Mode and Effects Analysis (FMEA) and Critical Item List (CIL) will be provided to identify failure modes, determine their effect on engine and vehicle operation, and categorize them by criticality.

4.1.6 Environment

4.1.6.1 Ambient Conditions

Requirement. Verify that the turbopump is capable of withstanding ambient conditions as listed below, without failure or degradation of reliability:

Transportation/Storage Pressure
Static Firing Pressure
Launch Phase (Handling Phase) Pressure
Reentry/Landing Phase Pressure
Static Firing Temperature
Orbital Phase Ambient Conditions
Ferry Flight

Analysis. The turbopump components will be analyzed to determine compatibility with the ambient conditions listed above and extended durations (30 days) in an orbital environment. All metallic and nonmetallic materials used in the engine design will be reviewed to ensure no adverse effects from exposure to the specified environmental requirements.

4.1.6.2 Storage Conditions

Requirement. To verify that the turbopump shall suffer no degradation of reliability or operating life during its storage period.

Analysis. The turbopump assembly and all of its components will be analyzed relative to long term storage capability. The analysis will consist of review of the storage methods and packaging provisions. Evaluation throughout the design verification period will be utilized wherever applicable to identify specific storage problems and maintenance requirements. In addition, storage information compiled from other rocket engine programs will be utilized where applicable.

4.1.6.3 Thermal

Requirement. To verify that the turbopump is capable of withstanding the thermal exposure conditions experienced during the Launch, Orbital and Reentry/Landing phases without failure or degradation of reliability.

Analysis. The thermal limitations of the turbopump will be analyzed with respect to those conditions defined by SSME Base Heating.

4.1.6.4 Vibration, Shock, and Acoustic

Requirement. To verify that the turbopump has the capability to withstand the environmental loads specified in Section 3 and associated with the following operations without detrimental deformation, structural failure or degradation of reliability.

Ground Handling Loads (Turbopump not on engine)
Static Firing Acoustic Launch Phase Vibration/Shock/Acoustic and Acceleration
Reentry/Landing Phase Vibration/Shock/ Acoustic
Ferry Flight

Analysis. An analysis of the turbopump will be conducted to verify that the ability to withstand the environmental loads for operations given above are within the capability of the turbopump overall structural design.

4.1.6.5 Contamination

Requirement. To verify that the potential sources of contamination during hardware fabrication and turbopump assembly will be avoided, that turbopump self generated contamination will meet interface requirements, and that the turbopump has the capability to withstand any self generated contamination and the introduction of contamination upstream of the turbopump interface.

Analysis. A Contamination Control Plan will be provided to address all sources and requirements for contamination control.

Verification Complete Criteria. Verification will be considered complete when the Contamination control Plan has been submitted and implemented.

4.1.6.6 Moisture

Requirement. To verify that protection provided within the engine propellant feed system will prevent moisture from existing in all areas susceptible to moisture for all modes of operation.

Analysis. Engine system purges and operating procedures will be analyzed to assure that moisture will not exist in all areas susceptible to moisture.

Verification Complete Criteria. Verification will be complete when the specified analysis has been completed, and it has been shown that moisture will not exist in the areas of concern.

4.1.6.7 Fungus Resistance

Requirement. To verify that fungus nutrient materials are not used in the turbopump.

Analysis. An analysis of all turbopump materials will be performed to assure that no fungus nutrient materials are incorporated in the assembly.

Verification Complete Criteria. Verification will be complete when the specified analysis has been completed and it has been shown that no fungus nutrient materials are used in the turbopump.

4.1.7 Design Criteria

4.1.7.1 Structural Criteria. The structural design criteria to be used in the design of the HPFTP shall be per approved P&W procedures and shall satisfy the design requirements as specified in Section 3.

4.1.7.2 Safety Factor Criteria

Requirement. To verify that the components of the turbopump satisfy the safety factor criteria specified in Section 3.

Analysis. Analyses will be conducted to ensure that all turbopump components satisfy the safety factor requirements for the most critical expected operating conditions.

4.1.7.3 Limit Pressure

Requirements. To verify that the Limit Pressure values have been established for the turbopump in accordance with the requirements specified in Section 3.

Analysis. An analysis will be made to ensure that all characteristics which comprise the worst operational environment have been considered in establishing the Limit Pressure values.

4.1.7.4 Proof and Burst Pressure

Requirement. To verify that the proof pressure as specified for the turbopump has been established in accordance with the requirements specified in Section 3.

Analysis. An analysis will be performed using the applicable limit pressure, checkout pressure and the analysis results to determine if the correct proof values have been determined.

4.1.7.5 Fatigue Criteria

Requirement. To verify that the components of the turbopump satisfy the fatigue criteria specified in Section 3.

Analysis. Analysis will be conducted to ensure that all turbopump components satisfy the fatigue requirements for the most critical expected operating conditions. The fatigue life will be determined by comparing the calculated stresses and strains to the minimum material properties.

Strains and natural frequencies measured during laboratory and subsequent testing will be correlated to the calculated stresses, strains and natural frequencies to assure the proper fatigue life and safety factors exist. Where measured strain levels and natural frequencies are not available, the verification of fatigue life will be based on analytical analyses only.

4.1.8 P&W Military Specifications

4.1.8.1 Standards

Requirement. To verify the turbopump design requirements for standards.

Analysis. The specified turbopump requirements will be verified by reviewing and correlating the engineering drawings and specifications with all applicable documents of Section 2. It will be assured that the requirements have been followed and are properly documented and implemented. Drawing stack-ups will also be accomplished, where applicable, to assure that the requirements have been met at the drawing tolerance extremes.

Statistical evaluation of these results will be used for verification of functional interchangeability.

4.1.9 Weight

4.1.9.1 The high pressure fuel turbopump design weight goal of 771 lbs will be verified by analysis of the detail parts through the design and development program. Physical dry weight measurements of the first detail parts received, analytically adjusted for the impact of the non flight instrumentation requirements will verify the weight of the first experimental assemblies. Final weight verification will be completed by the dry weight measurement of the production pumps at the detail and assembly level.

Verification of wet weight will be done by analysis.

4.1.10 Test Facilities

4.1.10.1 Pressure Test Facility. A pressure test facility shall be required to proof test the inlet, pump and rear housings and the turbine inlet duct. Testing shall require ambient temperature pressurants at various pressure levels on a single proof test and a hydraulic ram for thrust loading capability. Because of the high pressures involved, safety measures shall be required to protect personnel, test hardware, and the facility.

4.1.10.2 Vibration test Facilities. Vibration test facilities shall be required to determine.

a. Resonant frequencies of:

(1) Impeller
(2) Turbine inlet duct
(3) Turbine vanes
(4) Turnaround duct structure
(5) Turbine exit diffuser
(6) Turbine blades
(7) Lift-off seal
(8) Housings
(9) Turbine disk/shaft
(10) Turbine bladed rotor
(11) Turbine ducts and stators
(12) Housing assemblies
(13) Turbopump assembly

b. Rotor assembly free/free resonant frequencies

4.1.10.3 Spin Test Facilities. Spin test facilities shall be required to perform spin-stress and spin burst tests on the impellers, and turbine disks. Spin speeds to generate stresses sufficient to cause plastic deformation in the rotating elements shall be demonstrated.

4.1.10.4 Metallurgical Evaluation Facilities. Metallurgical evaluation of turbopump detail parts shall be required to evaluate fabrication processes. Analysis shall be performed on bearing outer races for depth of carburized case, and hardness of the case and core. EDM samples from the main housing volute and pre-machining test pieces shall be required to evaluate the depth of the recast layer to certify the machining process. Weld samples shall be evaluated to certify weld techniques and subsequent heat treatment on any part, if applicable. Existing facilities and analysis techniques shall be used. Applicable material tests (TMF, creep, tensile, etc.) will be conducted on all turbopump detail parts.

4.1.10.5 Bearing Environmental Test Facilities. Bearing evaluation and endurance testing shall be conducted in the P&W GPD liquid hydrogen test facility. A gaseous nitrogen drive system shall be used with speed requirements to 38,000 rpm. Liquid hydrogen at approximately 600 psig and a flow rate of approximately TBD per test bearing shall be required.

4.1.10.6 Water Flow Visualization Facility. Flow visualization and pressure measurement tests will be performed using, 1) a full-size transparent model of the turbine turnaround duct/hot gas manifold, and 2) a full scale model of the pump main inlet flowpath with a rotating impeller. These tests will be conducted at Marshall Space Flight Center (MSFC) in the Dynamic Fluid Flow (water) Facility or an equivalent test stand.

4.1.10.7 Air Flow Facility. Flow measurement tests will be performed using a full scale model of the turbine exit turnaround duct/hot gas manifold. These tests will measure the total static pressures along the hot gas flowpath from the turbine exit plane, through the fuel bowl racetrack. Dynamic (fluctuating) pressures will also be measured at selected locations in the flowpath. These tests will be conducted at Marshall Space Flight Center in the Dynamic Fluid Flow (Air) Facility.

4.1.10.8 Turbopump Test Facility. Structural, performance and endurance test evaluations of the complete HPFTP will be conducted in the P&W E-8 test facility. This test stand will utilize both facility STE and engine preburners to provide a hot gas supply to drive the HPFTP turbine and will incorporate a facility STE hot gas manifold for discharge gas collection and to provide geometric simulation of the engine interfaces. The use of SSME engine hardware to provide good engine simulation validates environmental evaluation of the turbine section during turbopump testing in the E-8 facility.

4.1.10.9 Engine Test Facility. Comprehensive turbopump environmental evaluation shall be accomplished with the engine system. Test facilities include the MSFC turbopump test bed engine stand, and test stands at NSTL.

4.2 Minimum Hardware Level(s) For Verification

4.2.1 Examination of Hardware. All HPFTP detail parts shall be subject to complete process, materials and dimensional inspections to verify compliance with the design requirements specified in Section III.

4.2.2 Minimum Hardware Level(s). A summary table of DVS level(s) at which design requirements and predicted environments can be adequately simulated and verified is presented on a preliminary basis in Section V of this DVS. This summary table will be updated by DVS document revisions as HPFTP design requirements and predicted environments are further refined.

4.3 Amount of Hardware/Number of Tests. The estimated number of verification tests required is given in Section 4.1, verification analysis and testing, of this DVS. Unless otherwise stated, detail DVS tests will be performed on only one part, subassembly and component DVS tests will be performed on only one set. Component DBS tests will be included in 14 builds of eight (8) pump units.

4.4 Verification of Analytical Tools

This section will be refined and updated by DVS document revisions as HPFTP design requirements and predicted environments are further defined.

4.4.1 General Description. Analysis methods used in the design of the ATD turbopumps have been specifically developed for, and tailored to lightweight/high-durability rotating turbomachinery. These methods listed in the Program Development Plan (FR19683-2) Tables 3-1 through 3-8, have been verified on similar turbomachinery hardware in ongoing military turbine engines and are directly applicable to the ATD turbopump hardware. The environmental effects on material strength of rocket peculiar parameters, such as high-pressure hydrogen, will be verified in laboratory evaluations and the design methods will reflect these influences.

The fluid coupling effect on rotordynamic stability and the computational fluid dynamics (CFD) effects on aerodynamic/hydraulic fluid flow are current technology areas which will require verification for ATD turbopump applications. Special rig investigations are planned to evaluate the influence of fluid-forcing functions on rotor dynamic stability, and the result generated on a separate ongoing CFD research contract will be fully applied to the ATD turbopump design.

4.4.2 Verification of the Damper Seal Stability Methods and Code. A damper seal analysis will be performed in support of the overall rotordynamic effort. The initial analyses will utilize a code developed by Dr. Dara W. Childs of Texas A&M University. This damper seal code has been previously used by Dr. Childs during his analysis of the current SSME turbopumps for NASA/MSFC. Dr. Childs is recognized as one of the leading authorities in turbomachinery rotordynamics and high-pressure cryogenic damper seal technology, with specific experience on the current SSME turbopumps. Dr. Childs has used empirical data gathered from his damper seal rig at Texas A&M using a halogen (HALON-CBrF3) for the fluid in the seal demonstrator damper seal rig tests to be conducted as part of the ATD development program. These tests will define the overall damping effectiveness and leakage rates of candidate seal configurations which are established using the Texas A&M code discussed above.

The demonstrator rig will define the damping effectiveness by quantifying changes in the rotor onset speed of instability (OSI) associated with different damper seal geometries. The baseline OSI will be generated with a rotor that has equivalent mass distribution and stiffness characteristics to the test rotor configurations, but with no attempt to impart supplemental damping. The rig instrumentation parameters associated with this demonstration concept include rotor speed and deflection, vibrations, and internal pressures and temperatures.

The damper seal rig will also be used for determining ball bearing radial springrates and damping. Bearing design will be the same as turbopump ball bearings. The rotor resonance will be measured and correlated with rotor modal testing and rotordynamic analysis to verify dynamic springrate.

4.4.3 Verification of Turbine Computational Flow Dynamics (CFD)

Application of the Computational Fluid Dynamics codes will be directed toward the following analyses:

1. Turnaround duct/diffuser/hot gas manifold flow integration
2. Bearing and seal cooling/circulation flow
3. Turbine rotor/stator aerodynamic/structural integration
4. Turbine inlet temperature distribution prediction
5. Turbine temperature profile attenuation
6. Pump inlet/inducer flow interaction
7. Pump impeller/crossover passage flow interaction

Validation of the codes for the turbine rotor/stator analyses requires measurement of the following parameters:

1. Time-resolved pressure distributions on the rotor and stator
2. Wake defect measurements
3. Fluid Particle path traces and unheated/heated flow fields

These measurements can be made on a large scale rig and do not have to be performed at full Reynolds number of Mach number. Use of data generated by Dring and Sharma et al at United Technologies Research Center, and the continuations of this ongoing work will provide the required data for code verification. Generation of the verification data will not be required as part of the ATD program. These tests are being conducted under separate funding. Data for verification of codes for the remaining analyses will come from available sources. Code verification, implementation at MSFC, and application will be with the assistance and participation of representatives of the MSFC Systems Dynamics Laboratory.

4.5 Verification Complete Criteria. This section of the preliminary HPFTP DVS will be defined and updated by DVS document revisions as HPFTP design requirements and predicted environments are further defined. An individual design requirement shall be considered complete when:

(1) The minimum number of turbopumps of the specified configuration performed within specification tolerances during/after required testing.

(2) The cause of out-of-specification conditions on all other turbopumps has been identified and other anomalies that occur, even though not related to the verification criteria, have been evaluated; and

(3) All identified unsatisfactory conditions related to design, manufacturing processes, and operation of the turbopump configuration being verified have been corrected and, if additional verification testing is deemed necessary, the conditions of (1) and (2) above have been met during such testing.

Completion of the verification of an individual design requirement will be documented on the format presented in Figure IV-2.

4.6 Verification Complete Package

A verification complete package containing the analysis, test data and supporting rationale for each DVS requirement shall be submitted 30 days after completion of each DVS requirement. Detailed analyses not supplied but developed in support of the ATD contract shall be supplied at the request of the procuring activity.

SECTION 5.0
REQUIREMENTS/VERIFICATION MATRIX

5.1 GENERAL

The high pressure fuel turbopump Requirements/Verifications matrix (Table V-1) provides correlation between design requirements and the tests required to verify that the requirements have been met. Each requirement is referenced to the paragraph number of all of the tests associated with that particular number.

Table V-1. High-Pressure Fuel Turbopump Verification Cross Reference Index

Method Legend

N/A	- Not Applicable	c	- Subassembly Test
a	- Analysis	d	- Component Test
b	- Detail Part Test	e	- Engine Test

Requirement (Section 3.0)		Verification Method (Section 4.0)				
		a	b	c	d	e
3.	Design Requirements					
3.1	Functional and Nonoperating Characteristics					
3.1.1	Functional Performance					
3.1.1.1	Power Levels	4.1.2.1			4.1.3.3, 4.1.3.3.2	4.1.3.4.1
3.1.1.2	Shutdown/Throttling/Step Change	4.1.2.1			4.1.3.3.2, 4.1.3.3.7	4.1.3.4.2
3.1.1.3	Starts	4.1.2.1			4.1.3.3.2, 4.1.3.3.7	4.1.3.4.2
3.1.1.4	RPL/MPL Duration	4.1.2.1				4.1.4.4.1.5
3.1.1.5	FPL Duration	4.1.2.1				4.1.4.4.1.5
3.1.1.6	Propellant	4.1.2.1			4.1.3.3.2	4.1.3.4.2
3.1.1.7	Leakage	4.1.2.13			4.1.3.3.2, 4.1.4.3.2.1	
3.1.1.8	Prelaunch Conditioning Duration				4.1.3.3.6	
3.1.1.9	Prelaunch Service Free Duration				4.1.3.3.6	
3.1.1.10	Duty Cycle					4.1.4.4.1.5
3.1.1.11	Drying Purge				4.1.3.3.2, 4.1.4.3.1.7	
3.1.1.12	Thermal Insulation			4.1.4.2.6.1	4.1.3.3.2, 4.1.4.3.2.2	4.1.3.4.2
3.1.1.13	Breakaway Torque	4.1.2.2, 4.1.5.1			4.1.3.3.2	4.1.3.4.2
3.1.1.14	Functional Interface	4.1.2.2, 4.1.5.1			4.1.3.3.2	
3.1.2	HPFTP Hardware Characteristics					
3.1.2.1	Detail Parts					
3.1.2.1.1	Main Housings					
3.1.2.1.1.1	Membrane Stresses	4.1.2.9	4.1.4.1.1.1			
3.1.2.1.1.2	Stress Rupture	4.1.2.9	4.1.4.1.1.1			
3.1.2.1.1.3	Resonant Vibration	4.1.2.9	4.1.4.1.1.2		4.1.4.3.1.1, 4.1.4.3.2.2	4.1.4.4.1.1
3.1.2.1.1.4	Fabrication	4.1.5.2	4.1.4.1.1.3			
3.1.2.1.2	Internal Pump Housings/Diffusers					
3.1.2.1.2.1	Membrane Stresses	4.1.2.9	4.1.4.1.1.1			
3.1.2.1.2.2	Stress Rupture	4.1.2.9	4.1.4.1.1.1			
3.1.2.1.2.3	Resonant Vibration	4.1.2.9	4.1.4.1.1.2			4.1.3.4.2
3.1.2.1.2.4	Fabrication	4.1.5.2	4.1.4.1.1.4			
3.1.2.1.3	Impellers					
3.1.2.1.3.1	Plastic Deformation	4.1.2.9	4.1.4.1.3.1, 4.1.4.1.3.2			
3.1.2.1.3.2	Burst Speed	4.1.2.9	4.1.4.1.3.3			
3.1.2.1.3.3	Vibration	4.1.2.9	4.1.4.1.3.4			

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Table V-1. High-Pressure Fuel Turbopump Verification Cross Reference Index (Continued)

Method Legend

N/A	- Not Applicable	c	- Subassembly Test
a	- Analysis	d	- Component Test
b	- Detail Part Test	e	- Engine Test

	Requirement (Section 3.0)	Verification Method (Section 4.0) a	b	c	d	e
3.1.2.1.3.4	Fabrication	4.1.5.2	4.1.4.1.3.5			
3.1.2.1.4	Pump Section Ball Bearing					
3.1.2.1.4.1	B1 Life	4.1.2.7	4.1.4.1.2.2, 4.1.4.1.2.4			
3.1.2.1.4.2	Lubrication Transfer Efficiency	4.1.2.7	4.1.4.1.2.2, 4.1.4.1.2.4			
3.1.2.1.4.3	Heat Generation	4.1.2.7				
3.1.2.1.5	Turbine Section Roller Bearing					
3.1.2.1.5.1	B1 Life	4.1.2.7	4.1.4.1.2.2, 4.1.4.1.2.3			
3.1.2.1.5.2	Lubricant Transfer Efficiency	4.1.2.7	4.1.4.1.2.2, 4.1.4.1.2.3			
3.1.2.1.5.3	Heat Generation	4.1.2.7				
3.1.2.1.6	Lift Off Seal					
3.1.2.1.6.1	Static Helium Leakage		4.1.4.1.4.1	4.1.3.2.3.1	4.1.3.3.2, 4.1.4.3.1.5	
3.1.2.1.6.2	Lift Off Pressure	4.1.2.9	4.1.4.1.4.1	4.1.3.2.3.1	4.1.4.3.1.5	
3.1.2.1.6.3	Operating Hydrogen Flow		4.1.4.1.4.1	4.1.3.2.3.1	4.1.4	
3.1.2.1.6.4	Reseat Pressure	4.1.2.9	4.1.4.1.4.1	4.1.3.2.3.1		
3.1.2.1.6.5	Cyclic Life	4.1.2.9	4.1.4.1.4.1, 4.1.4.1.4.2			
3.1.2.1.6.6	Vibration	4.1.2.9	4.1.4.1.4.1, 4.1.4.1.4.2			
3.1.2.1.7	Turbine Disk/Shaft					
3.1.2.1.7.1	Plastic Deformation	4.1.2.9	4.1.4.1.7.1, 4.1.4.1.7.2			
3.1.2.1.7.2	Burst Speed	4.1.2.9	4.1.4.1.7.3			
3.1.2.1.7.3	Vibration	4.1.2.9	4.1.4.1.7.4			
3.1.2.1.7.4	Fatigue Life	4.1.2.9	4.1.4.1.7.1			
3.1.2.1.8	Turbine Blades					
3.1.2.1.8.1	Vibration	4.1.2.9	4.1.4.1.8.2	4.1.4.2.4.1		
3.1.2.1.8.2	Fatigue Life	4.1.2.9	4.1.4.1.8.3			
3.1.2.1.9	Turbine Vanes					
3.1.2.1.9.1	Vane Vibration	4.1.2.9	4.1.4.1.9.1			
3.1.2.1.9.2	Platform Vibration	4.1.2.9	4.1.4.1.9.1			
3.1.2.1.9.3	Fatigue Life	4.1.2.9	4.1.4.1.9.2			
3.1.2.1.10	Turbine Inlet Duct					
3.1.2.1.10.1	Membrane Stresses	4.1.2.9	4.1.4.1.5.1			
3.1.2.1.10.2	Stress Rupture	4.1.2.9				
3.1.2.1.10.3	Vibration	4.1.2.9	4.1.4.1.5.2			
3.1.2.1.10.4	Fatigue Life					
3.1.2.1.11	Turbine Turnaround Duct					
3.1.2.1.11.1	Membrane Stresses	4.1.2.9	4.1.4.1.6.1			

Table V-1. High-Pressure Fuel Turbopump Verification Cross Reference Index (Continued)

Method Legend

N/A	- Not Applicable	c	- Subassembly Test
a	- Analysis	d	- Component Test
b	- Detail Part Test	e	- Engine Test

	Requirement (Section 3.0)	Verification Method (Section 4.0) a	b	c	d	e
3.1.2.1.11.2	Stress Rupture	4.1.2.9				
3.1.2.1.11.3	Vibration	4.1.2.9	4.1.4.1.6.2			
3.1.2.1.11.4	Fatigue Life					
3.1.2.2	Subassembly					
3.1.2.2.1	Pump Section Ball Bearing Support System					
3.1.2.2.1.1	Spring Rate	4.1.2.7	4.1.4.1.1.3	4.1.4.2.1.1		
3.1.2.2.2	Turbine Section Roller Bearing Support System					
3.1.2.2.2.1	Spring Rate	4.1.2.7		4.1.4.2.2.1		
3.1.2.2.3	HPFTP Rotor Assembly					
3.1.2.2.3.1	Rotordynamic Stability	4.1.2.10, 4.4.2		4.1.4.2.3.1		
3.1.2.2.3.2	Unbalance	4.1.2.10				
3.1.2.2.4	Turbine Gas Path	4.1.2.4, 4.1.2.11	4.1.3.1.1	4.1.3.2.4.1, 4.1.3.2.5	4.1.3.3, 4.1.4.3	4.1.3.4, 4.1.4.4
3.1.2.2.4.1	Flow Discrepancies	4.1.2.4				
3.1.2.2.4.2	Foreign Object Damage Resistance	4.1.2.12				
3.1.2.2.5	Impeller Inlet Flowpath	4.1.2.3	4.1.3.2.1		4.1.3.3, 4.1.4.3	4.1.3.4, 4.1.4.4
3.1.2.2.5.1	Flow Discrepancies	4.1.2.3	4.1.3.2.1.1			
3.1.2.2.6	Turbine Inlet Bellows Shield and Bellows Assy	4.1.2.9	4.1.4.1.10.2		4.1.3.3, 4.1.4.3	4.1.3.4, 4.1.4.4
3.1.2.2.6.1	Vibration	4.1.2.9				
3.1.2.2.7	Damper Seal					
3.1.2.2.7.1	Functional Performance	4.1.2.8, 4.1.2.10		4.1.3.2.2.1		
3.1.2.3	Component				4.1.4.3	
3.1.2.3.1	Pump Performance	4.1.2.3			4.1.3.3.2, 4.1.3.3.3	4.1.3.4
3.1.2.3.1.1	Cavitation - Power Level				4.1.3.3.3	4.1.3.4.2
3.1.2.3.2	Turbopump Rotordynamic Stability				4.1.3.3.2, 4.1.3.3.3, 4.1.4.3.1.1, 4.1.4.3.1.5, 4.1.4.3.1.6	4.1.4.4.1.2
3.1.2.3.2.1	Nonsynchronous Rotor Whirl				4.1.4.3.1.1	4.1.4.4.1.1
3.1.2.3.2.2	Rotor Vibration				4.1.3.3.2, 4.1.4.3.1.1	4.1.4.4.1.1
3.1.2.3.3	Turbopump Axial Thrust Balance	4.1.2.6			4.1.3.3.7, 4.1.4.3.1.2	4.1.3.4, 4.1.4.4
3.1.2.3.3.1	Rotor Axial Thrust Balance				4.1.3.3.7, 4.1.4.3.1.2	
3.1.2.3.4	Turbopump Side Loads					
3.1.2.3.4.1	Hydrodynamic and Aerodynamic Side Loads					

Table V-1. High-Pressure Fuel Turbopump Verification Cross Reference Index (Continued)

<u>Method Legend</u>

N/A	- Not Applicable	c	- Subassembly Test
a	- Analysis	d	- Component Test
b	- Detail Part Test	e	- Engine Test

		Verification Method (Section 4.0)				
Requirement (Section 3.0)		a	b	c	d	e
3.2	Reliability, Maintainability, Safety & Quality					
3.2.1	Maintainability				4.1.5.7	
3.2.1.1	Interchangeability and Replaceability	4.1.5.1				
3.2.1.1.1	Physical Interchangeability	4.1.5.1				
3.2.1.1.2	Functional Interchangeability	4.1.2.2				
3.2.1.1.3	Manufacturing Processes	4.1.5.2				
3.2.1.2	Identification and Marking	4.1.5.3				
3.2.1.2.1	Turbopump	4.1.5.3				
3.2.1.2.2	Marking of Connections	4.1.5.3				
3.2.1.2.3	Packaging	4.1.5.3				
3.2.2	Reliability	4.1.5.4				
3.2.3	Safety	4.1.5.5				
3.2.4	Quality Assurance	4.1.5.6				
3.2.5	Physical Characteristics	4.1.9	4.1.9		4.1.9	
3.2.6	Inspection				4.1.5.7.1, 4.1.4.3	4.1.4.4
3.2.7	Checkout and Monitor				4.1.5.7.2, 4.1.4.3	4.1.4.4
3.2.8	Service				4.1.5.7.3, 4.1.4.3	4.1.4.4
3.2.9	Access				4.1.5.7.4, 4.1.4.3	4.1.4.4
3.2.10	Handling				4.1.5.7.5, 4.1.4.3	4.1.4.4
3.2.11	Repair				4.1.5.6.6, 4.1.4.3	4.1.4.4
3.3	Envronments				4.1.3.3, 4.1.4.3	4.1.3.4, 4.1.4.4
3.3.1	Ambient, Storage, and Exposure	4.1.6.1, 4.1.6.2				
3.3.2	Acceleration and Ground Handling	4.1.6.1, 4.1.6.2				
3.3.3	Thermal	4.1.6.3				
3.3.4	Vibration, Shock and Acoustic	4.1.6.4			4.1.4.3.2.2	
3.3.5	Corrosion	4.1.4.3.1.7, 4.1.6.2				
3.3.6	Contamination	4.1.6.5				
3.3.7	Moisture	4.1.6.6			4.1.4.3.1.7	
3.3.8	Fungus Resistance	4.1.6.7				
3.4	Design Criteria					
3.4.1	Structural Criteria	4.1.7.1				
3.5.1.1	Safety Factor Criteria	4.1.7.2				

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Table V-1. High-Pressure Fuel Turbopump Verification Cross Reference Index (Continued)

Method Legend

N/A	- Not Applicable	c	- Subassembly Test
a	- Analysis	d	- Component Test
b	- Detail Part Test	e	- Engine Test

		Verification Method (Section 4.0)				
	Requirement (Section 3.0)	a	b	c	d	e
3.4.1.2	Pressure Vessel Structural Criteria	4.1.7.3, 4.1.7.4				
3.4.1.2.1	Limit Conditions	4.1.7.3				
3.4.1.2.2	Proof Criteria	4.1.7.4				
3.4.1.2.3	Burst Criteria	4.1.7.4				
3.4.1.3	Fatigue Criteria	4.1.7.5				
3.4.1.4	Fracture Control Criteria	4.1.2.9				
3.5	P&W/Military Specifications & Standards					
3.5.1	P&W/Military Specifications and Standards					
3.5.2	Standards	4.1.8.1				
3.5.2.1	Parts	4.1.8.1				
3.5.2.2	Design	4.1.8.1				
3.5.2.3	Threads	4.1.8.1				
3.5.2.4	Parts List	4.1.8.1				
3.5.2.5	Dimensional Units	4.1.8.1				
3.5.2.6	Material properties	4.1.8.1				
3.5.2.7	Materials	4.1.8.1				
3.5.2.8	Processes	4.1.8.1				
3.5.2.9	Welding Process	4.1.8.1				
3.5.2.10	Parts and Material Program	4.1.8.1				
3.5.2.11	Flammability, LOX/GOX and Propellant	4.1.8.1				
3.5.2.12	Materials Selection List	4.1.8.1				
3.5.2.13	Hydrogen Embrittlement	4.1.8.1				
3.5.2.14	Braze Processes	4.1.8.1				
3.6	Failure Mode, Effect & Criticality Analysis	4.1.5.8				
3.6.1	Failure Mode, Effect & Criticality Analysis	4.1.5.8				
3.6.2	Safety	4.1.5.5				
3.6.3	Failsafe Design	4.1.5.5				
3.7	System and Design Analysis Results					
3.7.1	Design Verification Test Plan					
3.7.2	DVS Status Report					
3.7.3	Verification Complete Package					

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